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Effect of extreme pressure agents in cutting fluid on tool wear and surface finish

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EFFECT OF EXTREME PRESSURE AGENTS IN CUTTING FLUID ON TOOL WEAR AND SURFACE FINISH

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Abstract

To most tool engineers machinability connotes a combination of characteristics of a cutting operation which include: the life of a tool-work piece combination, the surface finish produced, the type of chip produced, and the power consumed in the formation of chips. The relative importance of these four characterisitics depends upon the nature of the operation that is being performed. The use of cutting fluids, lubricants at low speeds in particular, influence these characteristics favorably.

In this experiment the influence of extreme pressure lubricants is observed on tool wear and surface finish. From this experiment it can be concluded that E.P. agents, namely, chlorine and sulfur undoubtedly have effects on both of these characteristics. At the same time it is also observed that the degree of effectiveness of chlorine and sulfur both vary depending upon the cutting condition, i.e. cutting operation variables. It is realized that chlorine is basically an E.P. agent which is reactive under milder conditions while severe conditions favor sulfur as an active

E.P. agent. But it also seems that too much concentration of either of these E.P. agents may affect adversely on account of their destructive action on the tool material.

Introduction

A metal cutting fluid may be defined as any liquid or gas that is applied to the cutting tool to facilitate the removal of the metal by way of increasing the machining rate and the tool life and helping to produce a surface with satisfactory accuracy and finish (1). To various degrees any fluid applied to the machining operation will achieve these conditions by performing the following actions: Flow to the area of cutting action, wet the metal surfaces, remove heat and modify the friction between the surfaces with relative motion. Each one of these actions represent fluid properties which depend on a number of basic physical and chemical characteristics of the fluid.

The first property, flowing to the area of the cutting action, will depend largely on the viscosity of the fluid. Another factor controlling the fluid flow is the speed level at which the cutting operation is carried out (2). The wetting property will determine the degree with which the fluid directly contacts the metal surfaces, particularly in an adverse condition. Inherently then, cooling under such condition will also depend on the wetting property. In the absence of sufficient flow and wetting, a relocation of coolant jets to mechanically bring the fluid to the critical area of the cutting tool can sometimes cause a significant increase in tool life, especially in the high speed steel tool use (3).

In discussing the reduction of friction by cutting fluids, it is necessary to realize that practically all machining operations produce conditions which preclude thick film lubrication. Under the resulting boundary conditions, viscosity is a minor factor and oiliness is a major one. Under the extreme conditions, when even this regime can no longer carry the load and seizure, i.e. welding results, extreme pressure agents can be used. The action of the extreme pressure agents can be explained on the basis of different theories which will be reviewed later. The effect of the extreme pressure agents (better known as E.P. agents) is one of reducing friction. While ordinary boundary lubrication interposes some kind of thin film between the rubbing surfaces (2), and thus protects the surfaces against attrition, E.P. agents by their very action, which is usually called corrosion, destroy the metal surface (9,10).

These appear to be the major fluid properties of significance in metal cutting. For better understanding of the function of the cutting fluid it is helpful to review the function of a cutting tool.

Metal Cutting Mechanism and Cutting Fluid Performance:

Though it might be true in case of some brittle metals like cast iron, that the metal is cut in the fashion similar to the splitting of wood along the grain, it is not the case when machining the majority of metals (5). According to Pispanen and Ernst (6) during a metal cutting operation chips are formed by plastic deformation and tremendous power is required for this action. Approximately 97% of the total useful work done in the metal cutting is released in the form of heat (7). Fig. 1.

When the tool pushes through the metal, the atoms ahead of the cutting point are disturbed and begin to slide over the adjacent atoms. The friction involved in this sliding is called the "internal friction." When the tool continues to push through the metal, a chip is formed which eventually slides over the tool face where again the friction is encountered. This friction is called the "external friction." The work spent to overcome these frictions reappears as heat. With a freshly ground tool, it has been estimated that 60% of the total heat is liberated from the internal friction in the shear zone (A) (Fig. 1), approximately 30% is released in the chip tool zone (B) and approximately 10% released in the tool work zone (C). As the tool wears, undoubtedly the percentage of heat liberated will continuously vary (8).

Under certain cutting conditions the temperature and the pressure are high enough at the tool point to cause the material in tool and chips to be welded. Merchant (2) (Fig.2) depicts the idealized cross section of a portion of the chip-tool interface. It is seen that the chip and the tool are in contact at high spots where high pressures together with sliding motion generate friction and high heat. This causes localized welding of the chip to the tool. At the low speed cutting operations the worn cutting point of the tool and in high speed cutting operation the high level cutting speed itself are the causes of such high pressures and hence localized welding. The metal which gets welded to the tool and remains attached to the tool tip is called Built Up Edge (BUE). The built up edge is undesirable due to several reasons. Its continuous variation and ploughing leaves a rough finish on the machined surface. The ploughing along the tool face gives rise to the crater wear. Although the cutting point itself is protected by the small BUE, the other consequences stated make the BUE an undesirable phenomenon. One of several ways of preventing BUE (11), is the use of the cutting fluid which is of importance in the present discussion.

<u>Dry Friction Theory</u>

Frictional resistance due to interlocking of aspirities of the two sliding surfaces was interpreted by Amontous (1699). The proposed theory for frictional resistance due to formation of small welds at the points of contact of sliding surfaces, which was suggested by Holm in Sweden and Bowden and his co-workers in England, seems to be the most acceptable. Bowden and Taylor have pointed out that frictional resistance is not only due to localized welds but also attributed to the ploughing action of the high points of harder material through the softer material which makes the other surface of the sliding pair. The frictional resistance F may be expressed as:

$$F = \tau A_r + P$$

where τ = shear stress of the welds

A_r = real area of contact

P = ploughing component

Dividing this equation by the applied load for sliding, i.e. N, which further can be computed as the product of real area of contact A_r and hardness H of the aspirities we can express the above equation as:

$$\frac{F}{N} = \frac{\tau}{H} + \frac{P}{N}$$

$$\text{i.e. } \mu = \frac{\tau}{H} + \frac{P}{N}$$

where μ = coefficient of friction

The first term of the above equation represents the ratio of the shear stress to the hardness of the welds. This is the major component of the coefficient of friction. The other component i.e. P/N, the ploughing part of μ is appreciable only if a hard metal surface slides over a soft one (12).

It can be realized that when two surfaces of similar hardness slide against each other the value of the coefficient of friction can be brought down only if the component $\frac{\tau}{H}$ is reduced to a small value. This means a decrease in shear stress and an increase in hardness of the metal should be achieved. The low shear stress and high hardness is not a natural combination. So a lower coefficient of friction can be obtained only if a layered structure with low shear stress is created on the hard surface. This condition of a low shear stress layer with hard surface backing will give the required combination to lower the value of the coefficient of friction during sliding movement.

Out of the total power applied in a metal cutting operation 2/3 of it appears as heat generated at the shear plane. Most of the remaining power is utilized in overcoming external friction at the tool-chip interface. An equation can be constructed to represent total power applied (1):

$$P = F.V_f + S.V_s$$

where

P = Applied power

F = Friction force

V_f = Velocity of sliding

S = Shear force

V_s = Velocity of shear

The total power required for the cutting operation can be reduced by reducing both the terms on the right hand side of the equation, i.e. FV_f and SV_s.

The equation for the shear angle can be given (Merchant, 1942) by:

$$\Phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2}$$

where

Φ = Shear plane angle

α = Back rake angle

β = Friction angle

The above equation shows that a decrease in the friction angle increases the shear plane angle which in turn decreases the work in shear. This is true since an increased shear angle will result in a reduced shear plane area, assuming a constant shear stress. It is evident that if the friction between the tool and the chip can be reduced, the coefficient of friction can be so modified that it will result in a lower cutting power requirement; hence better cutting efficiency.

The improvement of the surface finish on the tool face, and the inclusion of certain materials such as sulfur or lead in the work material will improve machinability. The alteration of the metallographic structure of a work material by heat treatment is another method used to reduce the coefficient of friction. However, application of a cutting fluid in metal cutting is the method for reducing the coefficient of friction which will be the subject for this discussion.

Cutting Fluid Performance

Cutting fluids can be classified in two groups, namely, lubricants and coolants. Lubricants are those cutting fluids which will reduce the heat present during the operation by modifying the very source of heat generation, while coolants form that group of cutting fluids which will carry away the heat present. This can further be explained that lubricants, by reducing the coefficient of friction at the tool-chip interface, reduce the shear work required to bring plastic flow in the metal. Thus less initial power input is required. Consequently the total amount of heat is reduced. Thus lubricants will affect the rate of heat generated in the external as well as in the internal friction areas. Coolants on the other hand, with their physical properties such as, high specific heat, conductivity, and viscosity become the best means of carrying heat away from the cutting point of the tool.

The entire field of lubrication may be divided into three general regimes, which may be designated as the full fluid, boundary, and extreme boundary regions of lubrication. Full fluid lubrication which is also known as hydrodynamic lubrication, is not present in a metal cutting operation. This is due to the fact that, this type of lubrication condition requires positive pressure to be developed hydrodynamically. Lubrication of a metal cutting tool by a cutting fluid, lubricants, is either of the boundary or of the extreme boundary type, depending upon whether the temperature and the pressure developed are low and high respectively.

Under the severe conditions of temperature and pressure encountered on the face of a tool in a metal cutting operation it is found that the absorbed liquid films are incapable of withstanding the high shearing forces to which they are subjected. Only solid films are capable of remaining attached to the sliding surfaces to prevent metal-to-metal contact (1). Since the mechanism of chip formation yields a surface that is composed of minute hills and valleys on the chip surface, a labyrinth of fine capillaries is formed in conjunction with the tool surface. The surface tension of the cutting fluid then provides the driving force necessary to conduct the fluid to the cutting point against the outward motion of the chip. The fact that a cutting fluid in vapor phase is as effective as the fluid in liquid phase indicates that the action of cutting fluids in metal cutting is chemical rather than physical in nature.

The several combinations of conditions to which the cutting fluid is subjected, encourage the chemical action. Such conditions are:

1. Very high localized temperature--approaching the melting point of the metal being cut.
2. Very high pressure-- up to the hardness of the metal being cut.
3. Clean highly reactive nascent metal surface of the chip which is free from any oxide or any contamination.
4. Highly stressed metal.

The coefficient of friction of mineral oils under boundary conditions can be reduced by incorporation of certain additives such as fatty acids, which have polar molecules. This property of giving low coefficient of friction is known as oiliness. The theory of metallic soaps is the modification of the old physical absorption theory. A metallic soap is the chemical product resulting from the attack of polar molecules on the metal surface. In many practical examples of boundary lubrication, the conditions are mild enough to form metallic soaps. In other cases, conditions are so severe that temperatures far in excess of the melting point of metallic soaps are reached. In these conditions extreme pressure lubrication is required. The effective method of meeting such lubrication is to create relatively infusible solid films with low shear strength between the rubbing surfaces. These types of film are produced by either sulfide or chlorides of metal, or a mixture of both, which are effective due to their high melting points. Such additives are known as extreme pressure agents.

The addition of E.P. agents influence the tool life in various ways. For better understanding of these influences, different modes of tool failures should be reviewed. The life of a cutting tool is controlled in three ways according to the mode of tool failure limited by 1) excessive heat, 2) gradual wear, and 3) welding.

Of these, the first factor, i.e. excessive heat, causes softening of the cutting point leading to the loss of the tool tip. This is preceded by some reduction in the cross section of the tool which weakens the tool structure and brings the tool life to an end. Beaubien and Cattaneo (4) have shown in their experiments that although lubricants have little effect in the heat reduction aspect of such cutting conditions, E.P. agents when added to the mineral oil have increased tool life significantly.

The interesting point that they bring out is the fact that the use of an E.P. agent reduces the shear work during the cutting operation while the friction work remains practically unchanged. This is true since at the shear plane area shear velocity remains the same while shear force is reduced. Hence lower shear work is required. Although the friction at the tool-chip interface is reduced to half, the friction velocity is doubled. This results in almost constant friction work.

The second factor which controls the tool life is the gradual wear. The tool dimensions gradually change affecting a slow change in the quality of the product produced, i.e. higher surface roughness and poorer dimensional accuracy. Beaubien and Cattaneo show that though reduction of friction is most desirable under these conditions, the addition of an E.P. agent has usually a small effect and more often result in rapid tool wear due to the corrosive action of the E.P. agents on the tool surface. Neat mineral oil proves to be a successful fluid under such circumstances.

The last mode of tool failure governing the tool life is welding, in which failure results due to ploughing of the BUE through the tool surface by the sliding chip. E.P. agents in oil have a pronounced effect on this mechanism, often increasing tool life by as much as 10 to 20 fold. Oil alone has no effect under such conditions.

Ernst and Merchant (13) in their investigation of the action of a cutting fluid noted that those materials, which increased the cutting ratio, (cutting ratio refers to ratio of chip length to the tool travel-- lower ratio indicates built up edge) chemically reacted with the chip. The most effective chemicals present in the cutting fluid and responsible for this chemical reaction were those which contained chlorine, sulfur or phosphorous. It was also found that as the cutting speed was increased the effectiveness of various chemicals was reduced. This depends on the chemical, its concentration as well as the metal being machined. Clyde A. Sluhan (11) reviews the fact that the percentage of chlorine, sulfur or phosphorous in a cutting oil is not the only indication of its activity. Often a lower percentage of loosely held sulfur can be more effective than a greater percentage of more tightly held sulfur. Also, the use of too much sulfur can cause faster flank wear than desired. According to Perry (14) sulfur may be added to the oil either as an element or in combined form, e.g.

sulfurized fats. Chlorine, however, must always be added in combined form. Commercial cutting fluids of the oil type, developed primarily for friction reduction, contain fats, fatty acids, chlorine, sulfur or phosphorous either alone or in combination. This type is used to increase the tool life and improve the surface finish at relatively low speeds (below 200 sfpm). Bowden concludes that fats or fatty acids are mild lubricants by virtue of their good wetting action and by the reaction with the metal, they form metal soaps. These are effective under the temperature near their melting point, i.e. approximately 100°C. The works of Merchant (2) and Shaw (1) show chlorine as an excellent friction reducing material capable of reducing friction by 80%. Friction reducing effects depend upon the formation of ferric chloride film which is stable up to at least 300°C. Sulfur compounds capable of reacting with a metal surface are good boundary lubricants on metals like steel, copper and cadmium, but not silver and platinum. Phosphorous compounds react to form a low melting eutectic to provide the boundary film which reduces mechanical abrasion (15).

Prutton (16) and his co-workers review lubrication theory and explain the synergistic effect of a combination of chlorine and sulfur additives in extreme pressure lubricants. It is shown that combination is more effective than either alone. He points out that ferrous chloride melts at 690°C and ferrous sulfide melts at 1200°C. Hence cutting oils containing both chloride and sulfur would be more effective at lower temperature conditions where the chlorine would be more effective and under higher temperature conditions sulfur would be more effective.

Action of E.P. Agents in Cutting Fluid

There are several theories suggested to explain the reduction of friction during metal cutting operations, involving metal cutting fluids and extreme pressure lubricants.

The American theory of Merchant (2) and Shaw rely on the formation of low shear strength solids along the tool-chip interface. According to this theory, when a fluid, either liquid or vapor, comes in contact with a clean metal surface, one or more layers are apt to be formed on the metal surface by the process refered to as adsorption. The two types of adsorption are:

1) physical adsorption-- by which the molecules in the fluid layer and those on the metal surface are held together by a molecule bond.

2) chemical adsorption-- in which much stronger valancy bond exists within the molecules.

It is the latter type, chemical adsorption, that exists at the tool-chip interface during a metal cutting operation with the application of cutting fluid. The fundamental difference between these two types of adsorption is the requirement of energy of activation, which must be supplied to start the adsorption. In a metal cutting operation the high temperatures encountered provide sufficient source for the required energy of activation. The fluid film thus formed will reduce the friction between the tool-chip interface due to its low shear strength.

Kohn (17), however, reviews the Russian theory of Rebinder et. al. of the effect of surface active agents. According to this theory the reduction of tool forces is attributed to the intensification of strain hardening in the cutting zone by these agents. The changes in the creep and fatigue characters of metals are due to adsorption of such agents. This hastens the strain hardening of the metal surface and lattice penetration of the decomposed lubricant molecules.

After reviewing both the American and Russian theories Kohn (18) suggests the theory of microcrack stabilization to interpret the results of his experiments. Accordingly, the reduction in the tool wear, the friction at the tool-chip interface and the metal transfer of sliding surfaces is neither due to formation of low shear strength boundaries along the tool-chip interface, nor due to the acceleration of the strain hardening. It is due to generation of products such as ferricchlorides, formed during creation of fresh metal surfaces in the presence of lubricants which stablize microcracks generated prior to shear failure. Stabilization by the lubricant is attributed to its ability to reduce the micro crack surface free energy by coating its walls and thus spontaneously generating shear at a reduced stress level. An alternate mechanism to explain microcrack stabilization during deformation is through the promotion of dislocation pile-ups at the metal surface caused by a coating of the lubricant. The greater the lubricant's effectiveness in restricting the egress of dislocations, the greater is its effectiveness in promoting microcrack formation. The microcracks thus formed will lead to the shear failure of the work piece ahead of the tool tip and also cause the shear failure of numerous welded aspirities arising during chip flow over the tool face. Thus both the shear failures take place at the reduced stress level.

Hence it can be surmised that the reactivity of different cutting fluids will vary depending upon the amounts of chlorine, sulfur and phosphorus, their degree of chemical stability, the kind of metal they are used on, and speed feed relation in the cutting operation. The important characteristics of a cutting operation include: the life of a tool, the surface finish produced, the type of chip produced and the power consumed. Out of these four, tool wear and the surface finish were studied in this experiment.

Experimental Procedure

The purpose of this experiment was to study the effect of the concentration of chlorine and sulfur, individually as well as together in the cutting fluids on the tool wear and the surface finish during a series of metal cutting operations. For this purpose six different cutting conditions were selected--one dry, i.e. with atmospheric air as the cutting fluid and the rest of the five with water soluble chemical fluids as the cutting fluids. These were as follows:

1) a lower level concentration of chlorine of 11% in combined form.
2) a higher level chlorine concentration of 22% in combined form.
3) a lower level sulfur concentration of 3%.
4) a higher level sulfur concentration of 4.5%.
5) a combination of lower level concentrations of chlorine and sulfur, i.e. a mixture of (1) and (2) in the present case.

Cutting fluids were prepared by mixing one part of the chemical fluid and ten parts of water. The specifications of each fluid is given in Appendix-A.

The whole experiment is divided into two cutting conditions, namely, rough machining and finish machining. Turning on an engine lathe was taken as the machining operation. The work material used was SAE 1117. The tool material used was HSS, T-15. The tool geometry appears in Appendix- A.

Under each of the two machining conditions the feed and the depth of cut were kept constant while three different levels of speed were selected. In order to observe the relationship between the time of cut and the tool wear as well as the surface finish, it was desired that the measurement of the tool wear and the finish of the turned surface of the work material be taken at three different time periods before the tool failure occurs. A pilot experiment was carried out. The purpose of which was to determine the definite levels of feed, depth of cut, speed and time interval for the measurements, to avoid the situation where the tool fails during the last time interval of cut. Consideration was given to the different levels of various cutting variables so that adequate and measurable differences would be obtained.

As the result of this pilot experiment, the main experiment was designed in the following pattern:

1) <u>Roughing Condition</u>:

Feed = 0.020"/revolution

Depth of cut = 0.100"

Speeds = 50 sfpm, 100 sfpm, 150 sfpm

Time intervals for cut = 3 min., 5 min., and 9 min.

2) Finishing Condition:

Feed = 0.010"/revolution

Depth of cut = 0.050"

Speeds = 100 sfpm, 200 sfpm, 300 sfpm

Time intervals for cut = 3 min., 5 min., and 9 min.

Thus under each condition with 3 levels of speeds, 3 levels of time intervals, and 6 types of the cutting fluids, a total of 54 readings were taken to measure the tool wear and the work surface finish. In order to reduce the experimental error three replications were taken. This resulted in a sum total of 2 x 54 x 3 = 324 cuts. To further reduce the experimental error these cuts were taken in random fashion. Due to practical difficulty in changing the fluids each time for a different cut, which can arise if the whole experiment were randomized, randomization of readings was done within each of the cutting conditions. Thus, once the experimental set up was made for one cutting fluid, all necessary cuts under this condition were taken before switching over to the next cutting fluid.

The equipment used in this experiment is listed in Appendix-A. A frequency alternator coupled to the AC driven lathe provided a means of holding the cutting speed constant with variable workpiece size. The tool was placed on center at the start and the position was kept unchanged until the next set of tools was used which required recentering. During each cut, i.e. single combination of speed, feed and depth of cut, at the end of each time interval the tool was removed from the holder for the measurements. The tool wear was measured on a tool maker's microscope and the work surface finish was determined with a stylus type surface roughness measurement instrument. The tool wear was measured along the flank of the tool.

The following factors were considered during design and measurement stages of the experiment:

1) Since the chemical fluids were extreme pressure lubricants the maximum speed was kept below 300 sfpm.
2) The flow of cutting fluid was directed as shown in figure 3(a) and the indirect application as in 3(b) was avoided. This was done to make sure that the cutting fluid had access to the tool tip.

3) While taking the measurement for the tool wear the built up edge developed on the tool tip, if any, was removed.

Results

Appendix-B shows the measurements of the tool wear and the surface finish taken under each condition with replications. The averaged values of the three replications of each cut are tabulated in Appendix-C.

From the design of the experiment described previously it is evident that the prime purpose of this experiment was to study the influence of the concentration of chlorine and sulfur in the cutting fluid, individually as well as together, on the tool wear and work surface finish. In addition, the important interactions of variables on the cutting operation were also studied. Such interactions were: (1) tool wear vs. cutting time, (2) surface finish vs. cutting time, (3) tool wear vs. speed, and (4) surface finish vs. speed. The results of these two factor-interactions are illustrated in Appendix-D.

The statistical analysis of variance was carried out to confirm the significance of the effects of the variables observed from the plots. This analysis is shown in Appendix-E. The criteria of significance is the F ratio, i.e. the ratio of the mean square of effect under comparison and the experimental error term. In the tables shown in Appendix-E the sign * shows the significance at 99% or 95% confidence level as the case may be.

Discussion of Results

Effect of chlorine on tool wear:

The position of the chlorine on the dry cut curve in plot 1-3, Appendix-D, indicates a lower wear was achieved with the application of chlorine as an extreme pressure lubricant in cutting conditions examined. In plot-1, the curve for the low level chlorine is situated above the curve for higher level chlorine throughout the cut, which is not the case found in plot-2 and 3, i.e. at the speed level of 100 sfpm and 150 sfpm. This may be attributed to a higher concentration of chlorine having a damaging effect on the tool material, and thus causing rapid wear at lower speed levels. Plots 4,5, and 6 for speed levels of 100 sfpm and 200 sfpm in finishing conditions show that the higher concentration of chlorine gives lower tool wear than the lower concentration application of chlorine. From these observations it can be deduced that during the application of lower chlorine concentration a lower energy of activation was required, than during higher concentration application of chlorine.

Effect of chlorine on surface finish:

In roughing conditions, the surface finish curve for low concentration of chlorine falls below that of the higher concentration. This shows that better surface is obtained with the lower concentration at low speeds. In plots 11 and 12 the higher concentration gives better surface finish. Since the analysis of variance for surface finish in roughing and finishing conditions shows that the cutting fluid effect is significant at 99% (Appendix-E), the conclusion, similar to that during tool wear, can also be drawn. In the plots for finishing conditions, plots 10, 11, and 12, the dry cut seems to give worse finish than with chlorine. This can be explained, in view of the fact that with a fluid application a smaller built up edge was found.

<u>Effect of sulfur on tool wear</u>:

Plots 1, 2, and 3 distinctly show that the concentration of sulfur in the fluid contributes nothing to reduce the tool wear. This confirms the inability of sulfur in solution to react at lower speeds. Within sulfur concentration uncertainty of effect of concentration is observed. In the finishing condition, i.e. plots 4, 5, and 6, only plot 6 shows that tool wear is reduced with sulfur application. From these observations it can be concluded that sulfur reacts effectively at higher cutting speed conditions, especially at speeds above 200 sfpm.

However, during the finishing conditions even higher concentrations of sulfur do not seem to give lower tool wear than that with low concentration. This may be the result of the higher concentration being too high to retard tool wear. The 99% significance level of effect of fluid in both roughing and finishing conditions permits this conclusion.

Effect of sulfur on surface finish:

The presence of sulfur in a cutting fluid tends to give better surface finish. This can be seen from the plots 10, 11, and 12, where the dry cut curve is higher than the curves for the sulfur concentrations. Even here the higher concentration does not seem to be superior to the lower concentration.

Effect of combined sulfurated-chlorinated fluid:

Throughout the experiment all the plots show that the effect of the fluid containing sulfur and chlorine remains intermediate compared to those fluids containing only chlorine or only sulfur. This can be explained on the basis that chlorine is active at lower speeds while sulfur is active at higher speeds.

Comparison of effects of chlorine and sulfurated fluids:

Plots 1, 2, and 3 show that the chlorinated fluid gives lower tool wear than the sulfurated fluid at lower speeds when compared separately at different levels of concentration. In the finishing condition only at 300 sfpm did the sulfurated fluids give lower tool wear than the chlorinated fluid at both the levels of concentration. This agrees with the previous studies that sulfur is effective in reducing tool-chip friction. Subsequently, it reduces tool wear, at higher cutting speed conditions. However, chlorine reacts favorably at lower cutting speeds.

Plot 13 represents tool wear vs. speed in a finishing condition at the end of 9 minutes of cut under three different cutting conditions, i.e. (1) dry, (2) using chlorinated fluid of low level concentration and (3) using sulfurated fluid of low concentration. This plot is particularly significant in the way that it shows the effect of the presence of chlorine and sulfur over speed ranges of 100 sfpm to 300 sfpm. At 100 sfpm the chlorine curve is situated below the sulfur curve indicating higher tool wear with the sulfurated fluid than with chlorinated fluid. Gradually the two curves interchange the position indicating sulfur being more effective than chlorine as the speed increases. Though both the curves have positive slopes, the slope of the curve for sulfur is less than that of the chlorine. Near the speed level of 300 sfpm the curves once again interchange showing more tool wear resulting with the use of sulfurated fluid compared to that with the use of the chlorinated fluid. This can be explained on the basis of the available literature that the lubricants, in metal cutting application, are effective at speed levels below 200 sfpm while above 200 sfpm coolants are more effective as the temperature failure of tool is predominant at speed levels higher than 200 sfpm. The BUE existing during the dry cut seems to protect the tool tip from excess wear while during the cuts, using cutting fluids, a very little BUE which was formed did a little towards the tool wear reduction and resulted in higher wear. The sudden increase in tool wear during dry cut near 300 sfpm speed level can be explained on the same basis on which the interchange of chlorine and sulfur curves near 300 sfpm was explained above.

Plot 14 clearly shows that at the low speed level application, chlorine gives better surface finish than sulfur and at the higher speed, sulfur gives a better surface finish than chlorine. It should also be noted that dry cut throughout the finishing condition gives the worst surface finish. This was due to a large BUE being continuously formed and broken by the moving chip. This leaves a rougher finish during the dry cut. The application of the lubricants reduces the size of the BUE being formed, resulting in lesser debris between the flank area of the tool and the work. As a result, better surface finish was obtained with the fluid application. At 300 sfpm the chlorine and the sulfur curves tend to converge, showing that at such higher speeds there exists no significant difference in surface finish achieved during dry cut and cuts with fluid application. The reason is that at higher speed, tool failure is attributed not to the gradual wear but to temperature.

Conclusion

From the preceding discussion, and from the results obtained, it can be concluded that:

(1) Chlorine and sulfur as E.P. agents are effective at speed levels below 300 sfpm with chlorine more effective at low speed levels, i.e. below 100 sfpm, while sulfur is the most active agent at speeds above 100 sfpm.

(2) Higher concentration of the E.P. agent is more effective than the lower concentration. However, too high a concentration may act adversely on the tool material giving rise to excessive wear.

(3) BUE helps in preventing excessive tool wear but leaves poor surface finish. Hence tool wear under dry conditions, when the larger BUE is formed, is lower than during the cutting fluid application and poorer surface finish is obtained under a dry condition than under a cutting fluid application.

Area of Future Study

During the literature survey for this experiment and also while conducting the experiment, the following areas could be suggested for future study:

(1) Effect of cutting fluid, particularly lubricants, on tool chip interface temperature, to study different temperature levels at which different E.P. agents become reactive.

(2) Effect of lubricants on forces acting on the tool from which the effect of lubricants on power reduction can be studied under various cutting conditions.

(3) The same experiment could be conducted using work materials of different hardness with the purpose of studying the relationships among various cutting variables.

Figure - 1

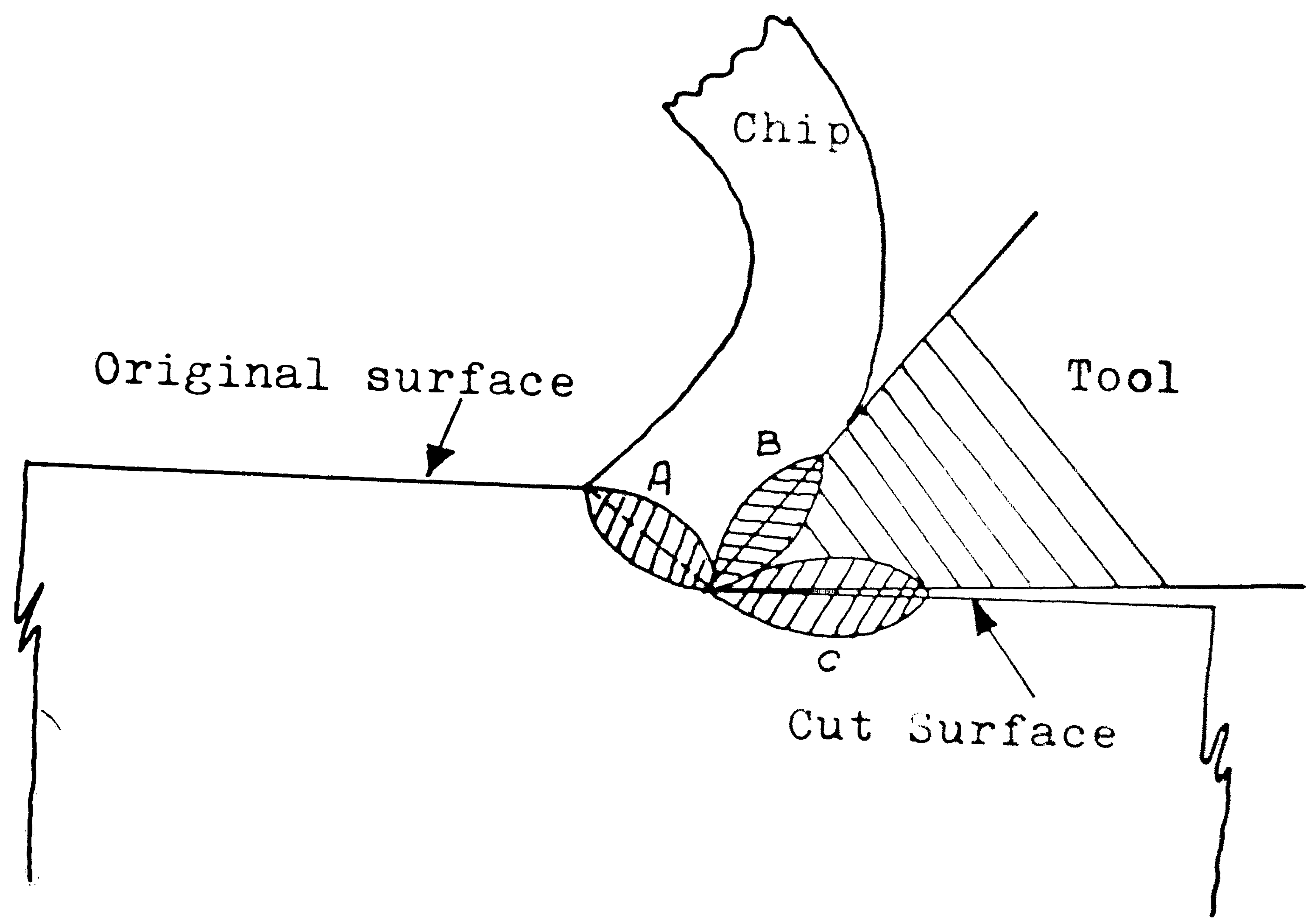


Figure - 2

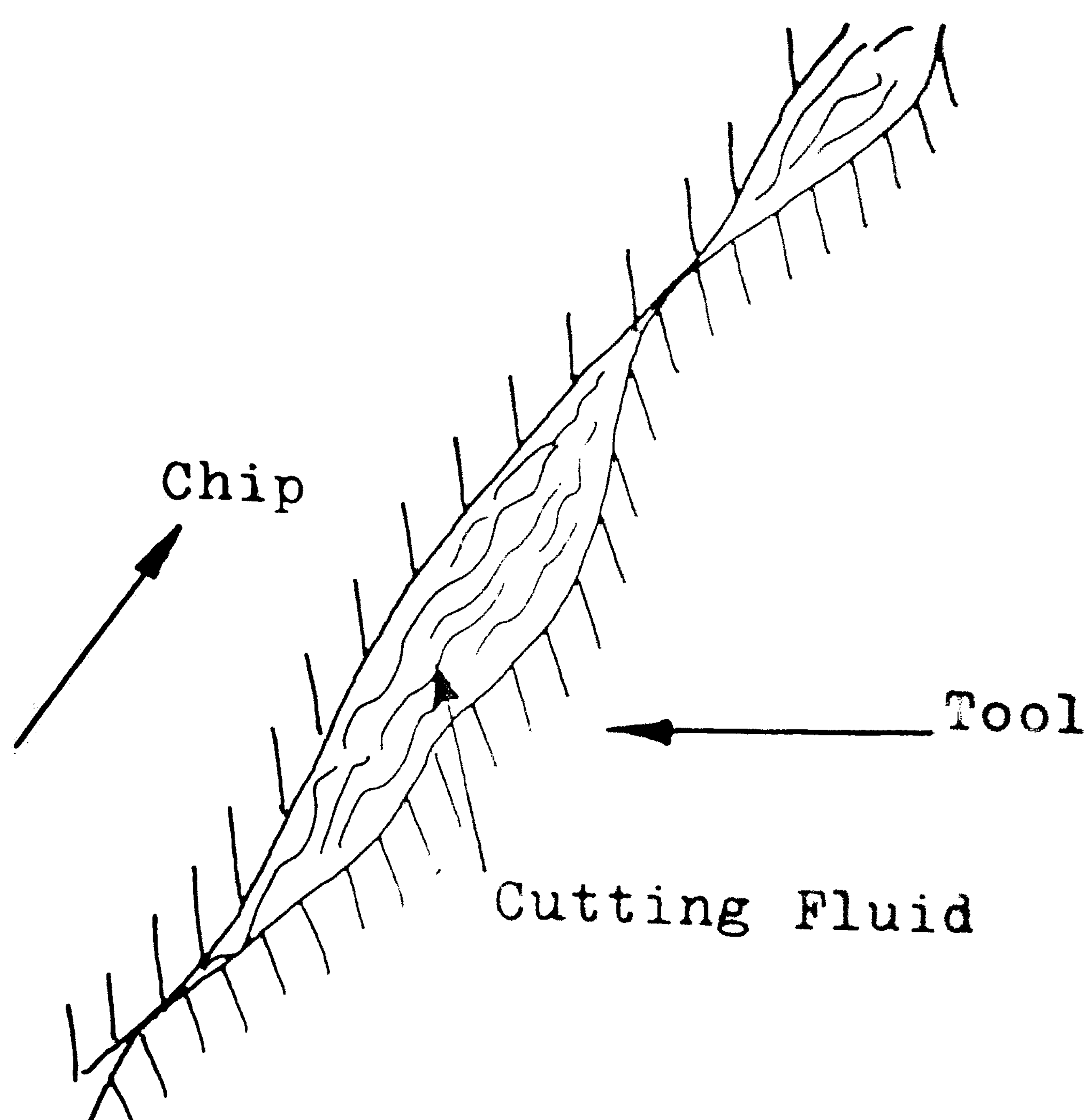
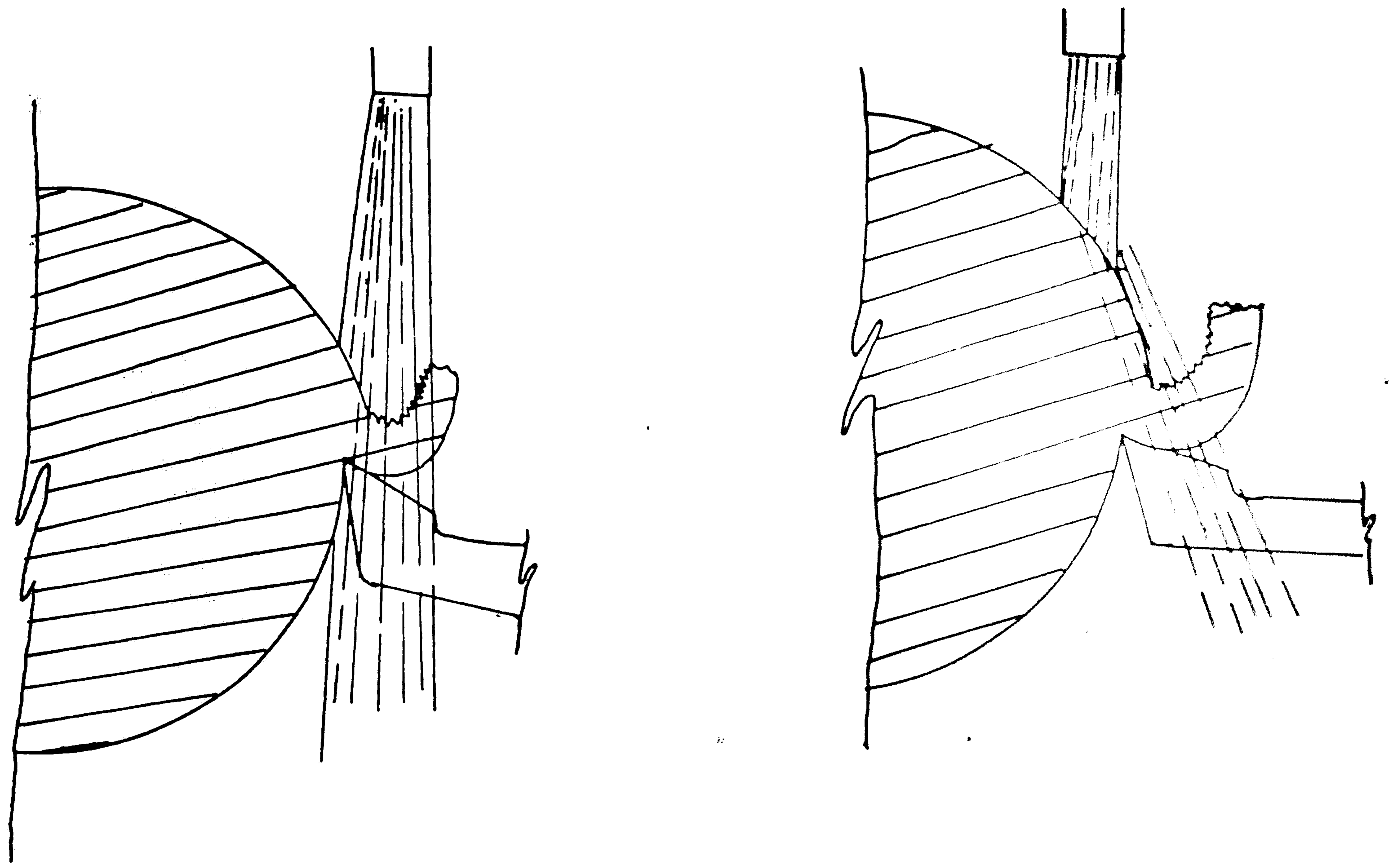


Figure - 3



(a)

Cutting Fluid directed on work and tool

(b)

Cutting Fluid deflects from the tool

Appendix - A

Equipment and Material

Equipment for experiment:

(1) 16" LeBlond heavy duty engine lathe with varydyne control

(2) Tool bit holder

(3) Toolmaker's microscope

(4) Stylus type surface indicator

Work Material:

SAE 1117

Tool Material:

HSS T-15

Tool Geometry:

0, 6, 11, 5, 15, 15, 3/64"

Chemical fluids for cutting operation:

(1)	TRIM RD-1-115	11% Chlorine in compound
(2)	TRIM RD-1-157	22% Chlorine in compound
(3)	TRIM RD-1-113C	3% Sulfur
(4)	TRIM RD-1-113D	4.5% Sulfu
(5)	TRIM RD-1-117	Chlorine 11% + Sulfur 3%

Appendix - B

Dry Cutting (Raw Data)

Feed = 0.020" Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.3	2.6	2.8	370	380	380
	3.4	4.5	5.0	360	400	380
	3.0	3.9	4.6	240	270	270
100	2.9	3.3	4.2	330	300	300
	3.4	4.0	4.8	260	260	270
	2.9	4.0	7.4	280	280	300
150	2.7	4.5	5.1	260	290	300
	5.9	6.5	7.1	240	260	320
	5.2	6.0	8.5	320	300	320

Feed =0.010" Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	1.4	2.0	2.5	200	200	200
	1.4	2.8	3.9	150	160	160
	2.8	4.0	4.2	400	400	450
200	2.1	2.9	4.0	140	160	190
	2.9	5.5	6.9	380	450	480
	3.0	5.8	5.9	260	300	300
300	6.5	11.2	30.0	110	120	120
	7.2	11.6	18.3	170	180	190
	5.5	6.5	6.5	250	250	300

Chlorine— Low Level (Raw Data)

Feed = 0.020″ Depth of Cut = 0.100″

Speed	Wear (10^{-3} inch) 3 min	Wear (10^{-3} inch) 5 min	Wear (10^{-3} inch) 9 min	Surface Roughness (μ inch) 3 min	Surface Roughness (μ inch) 5 min	Surface Roughness (μ inch) 9 min
50	2.4	2.5	3.5	410	420	520
	2.2	2.6	3.7	420	450	530
	3.1	4.0	4.4	500	520	560
100	3.0	3.7	4.5	450	450	460
	2.0	2.1	2.8	300	350	350
	2.6	4.0	6.0	560	560	560
150	2.4	2.4	3.0	360	350	350
	2.3	2.3	3.0	450	460	460
	3.4	3.4	4.8	440	460	500

Feed = 0.010″ Depth of Cut = 0.050″

Speed	Wear (10^{-3} inch) 3 min	Wear (10^{-3} inch) 5 min	Wear (10^{-3} inch) 9 min	Surface Roughness (μ inch) 3 min	Surface Roughness (μ inch) 5 min	Surface Roughness (μ inch) 9 min
100	2.9	3.3	3.3	160	150	160
	4.0	5.4	5.6	260	260	240
	3.8	4.3	5.3	140	150	150
200	6.8	7.3	7.9	280	280	290
	8.4	9.0	9.2	220	230	220
	8.6	10.0	10.4	260	240	220
300	9.0	9.3	9.3	200	220	240
	8.0	8.1	10.8	160	170	190
	7.5	8.9	9.8	150	160	160

Chlorine— High Level (Raw Data)

Feed = 0.020" Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.2	2.9	3.1	500	560	600
	2.3	2.4	3.0	520	620	640
	2.0	2.4	2.8	480	480	460
100	3.0	3.4	6.3	450	460	460
	3.1	3.8	4.6	350	350	390
	2.7	3.6	5.9	480	500	480
150	4.0	4.8	6.4	220	240	260
	3.8	5.5	8.5	500	520	520
	4.3	5.3	7.6	500	550	580

Feed = 0.010" Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	2.1	2.3	2.6	260	280	320
	2.1	2.5	3.6	200	280	300
	2.0	3.4	4.0	200	220	200
200	5.3	6.5	8.2	110	110	120
	4.5	4.7	5.3	160	170	160
	4.7	5.2	9.6	150	160	120
300	14.1	18.0	24.1	200	180	190
	12.2	15.8	27.0	120	140	150
	12.5	15.6	23.3	150	160	180

Sulfur-- Low Level (Raw Data)

Feed = 0.020"   Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.1	2.4	3.5	320	450	450
	4.2	4.6	6.4	500	540	540
	4.0	4.5	5.1	390	400	400
100	3.3	4.5	4.5	290	300	300
	3.8	4.0	5.4	380	390	400
	2.7	5.0	5.0	400	410	460
150	13.2	14.0	14.7	280	300	300
	18.6	18.6	20.6	280	300	320
	14.2	14.8	14.8	300	310	360

Feed = 0.010"   Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	6.8	7.0	7.1	220	220	250
	6.3	7.0	7.4	200	220	220
	3.3	3.6	4.2	210	220	250
200	6.6	7.0	8.5	170	170	190
	5.6	6.8	8.0	150	170	180
	6.1	6.4	7.3	150	170	190
300	5.6	6.4	9.2	170	190	190
	7.5	8.8	15.0	140	170	180
	9.4	9.6	16.2	140	170	200

Sulfur -- High Level (Raw Data)

Feed = 0.020"   Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.3	2.5	3.0	450	550	550
	2.2	2.6	2.7	450	450	500
	2.0	2.1	2.5	500	550	600
100	3.0	4.0	4.5	450	460	500
	3.4	4.0	4.8	460	480	480
	3.2	4.0	5.3	480	480	510
150	6.2	8.5	9.5	340	300	340
	6.3	7.6	10.1	460	500	550
	6.5	6.5	9.5	300	300	290

Feed = 0.010"   Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	2.5	3.0	4.0	290	320	380
	2.3	3.5	4.1	200	210	210
	3.5	4.0	4.3	280	290	320
200	2.6	4.4	7.1	150	120	120
	5.5	7.9	13.4	280	300	300
	5.2	7.2	7.8	110	120	110
300	9.7	11.4	21.1	180	180	180
	9.0	14.6	-	180	220	230
	9.5	10.4	-	150	180	200

Chlorine- Low Level + Sulfur- Low Level (Raw Data)

Feed = 0.020" Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.5	2.5	2.9	520	490	490
	2.5	3.0	4.7	530	540	560
	2.5	2.7	2.8	550	560	600
100	3.0	3.0	4.9	440	460	430
	3.4	3.7	5.6	420	420	440
	3.7	4.7	5.6	390	360	350
150	3.0	5.0	6.4	390	400	460
	4.0	4.2	5.3	280	310	320
	4.0	6.5	6.5	300	330	330

Feed = 0.010" Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	3.9	4.1	5.2	220	230	270
	3.0	3.2	4.0	260	200	280
	3.1	3.5	6.2	280	290	290
200	6.0	6.5	7.5	210	220	240
	5.1	5.2	5.7	170	180	180
	5.4	7.2	9.1	310	320	320
300	3.1	3.8	3.9	200	220	220
	4.0	4.6	5.1	160	180	190
	3.5	4.8	4.8	200	200	210

Appendix - C

Dry Cutting (Average)

Feed = 0.020"   Depth of Cut= 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.9	3.7	4.1	320	350	340
100	3.0	3.8	5.5	290	280	290
150	4.6	5.7	6.9	270	280	310

Feed = 0.010"   Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	1.9	2.9	3.5	250	250	270
200	2.7	4.7	5.6	260	300	320
300	6.4	9.8	18.3	180	180	200

Chlorine— Low level (Average)

Feed = 0.020"   Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.6	3.0	3.9	440	500	540
100	2.5	3.3	4.4	440	450	490
150	2.7	2.7	3.6	420	420	470

Feed = 0.010"   Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	3.9	4.3	4.7	190	190	180
200	8.0	8.8	9.2	250	250	240
300	8.1	8.8	10.0	170	180	200

Chlorine— High Level (Average)

Feed = 0.020"   Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.2	2.6	3.0	500	550	570
100	3.0	3.6	5.6	430	440	440
150	4.0	5.2	7.5	410	440	450

Feed = 0.010"   Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	2.1	2.7	3.7	220	260	270
200	4.8	5.5	7.7	140	140	130
300	13.0	16.5	24.8	160	160	170

Sulfur— Low Level (Average)

Feed = 0.020"   Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	3.4	3.8	5.0	300	460	460
100	3.3	4.5	5.0	360	370	390
150	15.3	15.8	16.7	290	300	330

Feed = 0.010"   Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	5.5	5.9	6.2	210	220	240
200	6.1	6.7	7.9	160	170	190
300	7.5	8.3	13.4	150	180	190

Sulfur— High Level (Average)

Feed = 0.020"   Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.2	2.4	2.7	470	520	550
100	3.2	4.0	4.9	460	370	390
150	6.3	7.5	9.7	370	370	390

Feed = 0.010"   Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	2.8	3.5	4.1	260	270	300
200	4.4	6.5	9.4	180	180	180
300	9.4	12.1	-	170	190	200

Chlorine— Low Level + Sulfur— Low Level (Average)

Feed = 0.020" Depth of Cut = 0.100"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
50	2.5	2.7	3.5	530	530	550
100	3.4	3.8	5.4	420	410	410
150	3.7	5.2	6.0	320	350	370

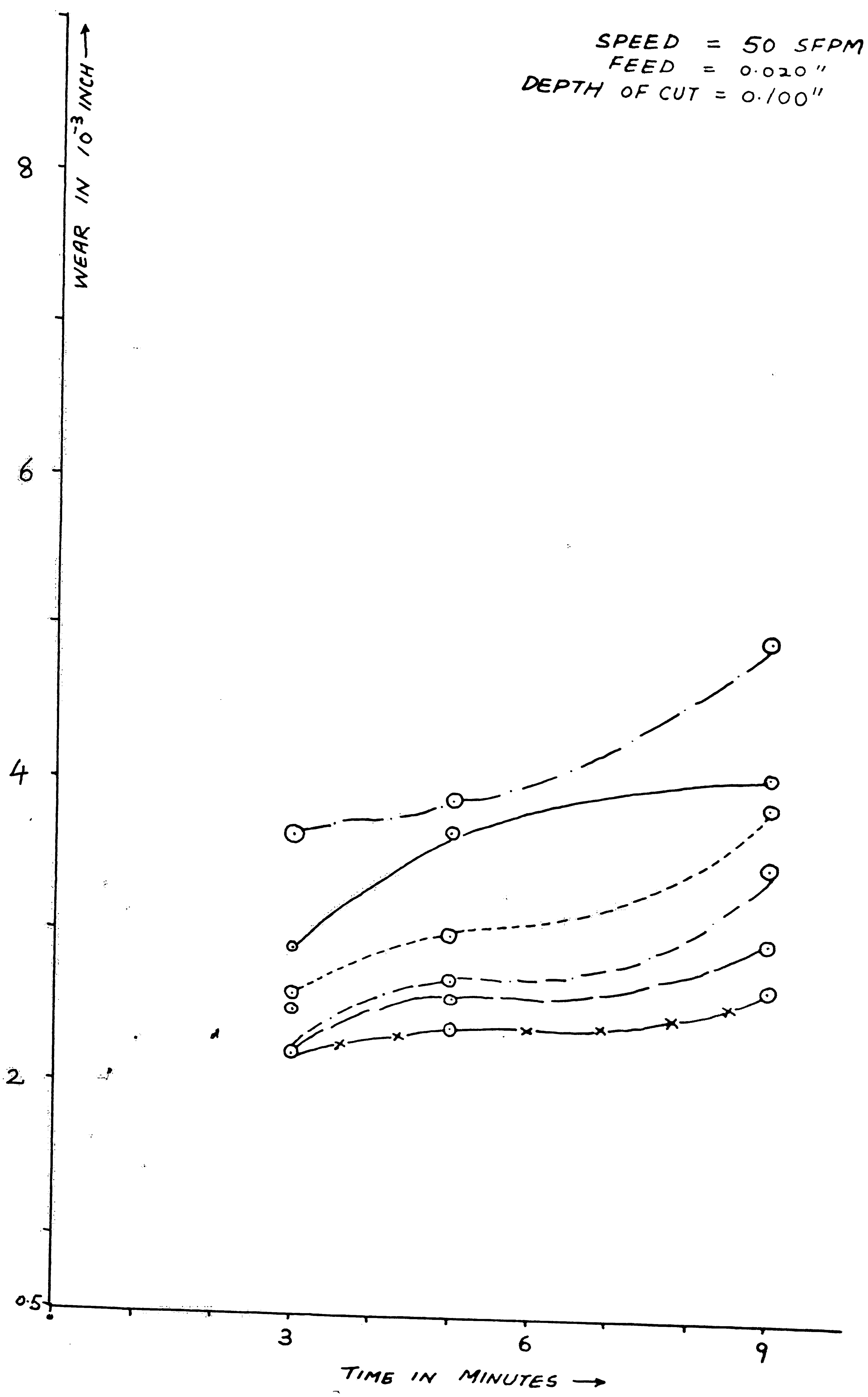
Feed = 0.010" Depth of Cut = 0.050"

Speed	Wear (10^{-3} inch)			Surface Roughness (μ inch)		
	3 min	5 min	9 min	3 min	5 min	9 min
100	3.3	3.6	5.1	250	240	270
200	5.5	6.3	7.4	230	240	250
300	3.5	4.4	4.6	190	200	210

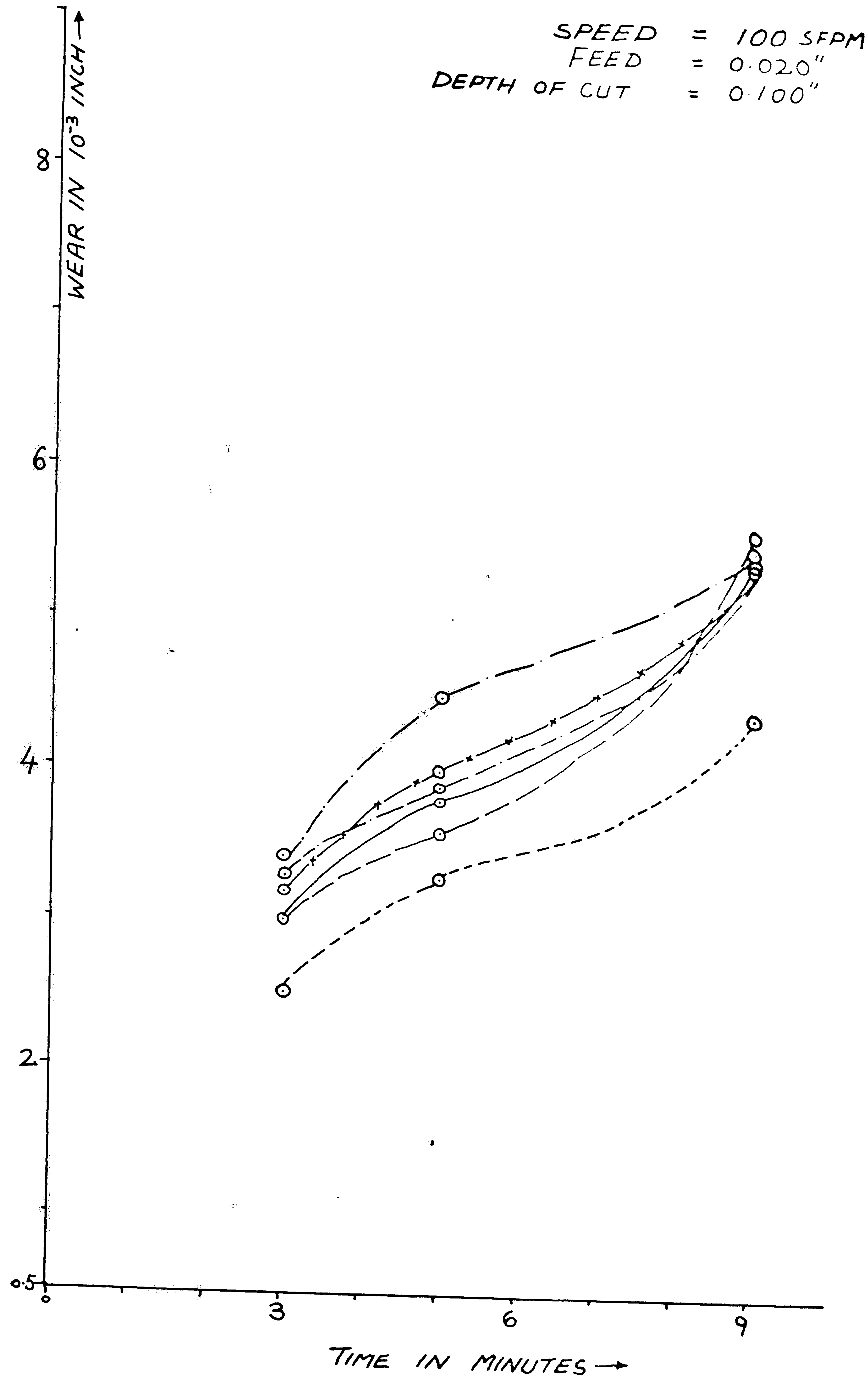
Appendix - D

LEGEND

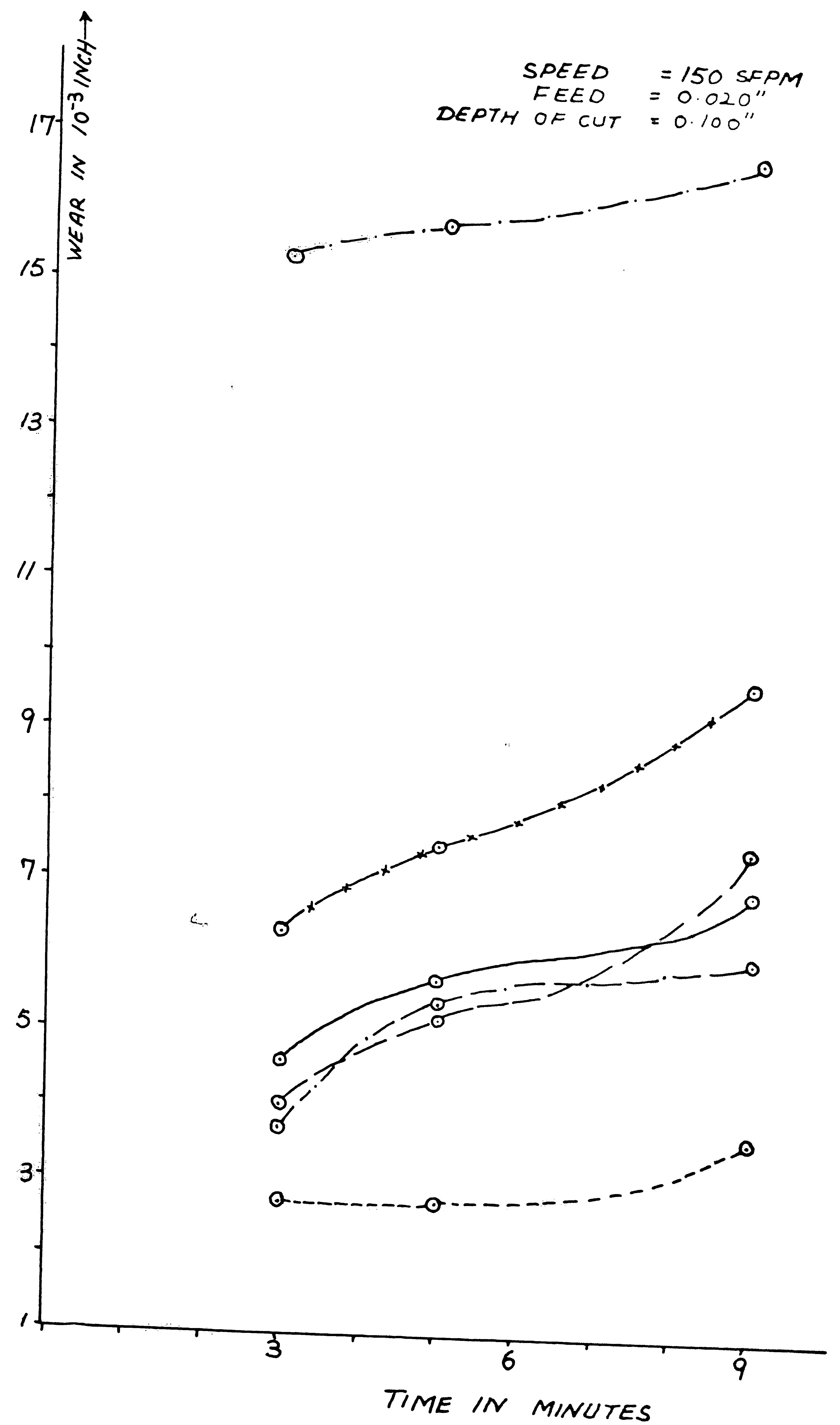
- Dry
- Chlorine - Low Level
- Chlorine - High Level
- Sulfur - Low Level
- Sulfur - High Level
- Chlorine - Low Level + Sulfur - Low Level


SPEED = 50 SFPM
FEED = 0.020"
DEPTH OF CUT = 0.100"
WEAR IN 10^{-3} INCH →
8
6
4
2
0.5
3
6
9
TIME IN MINUTES →

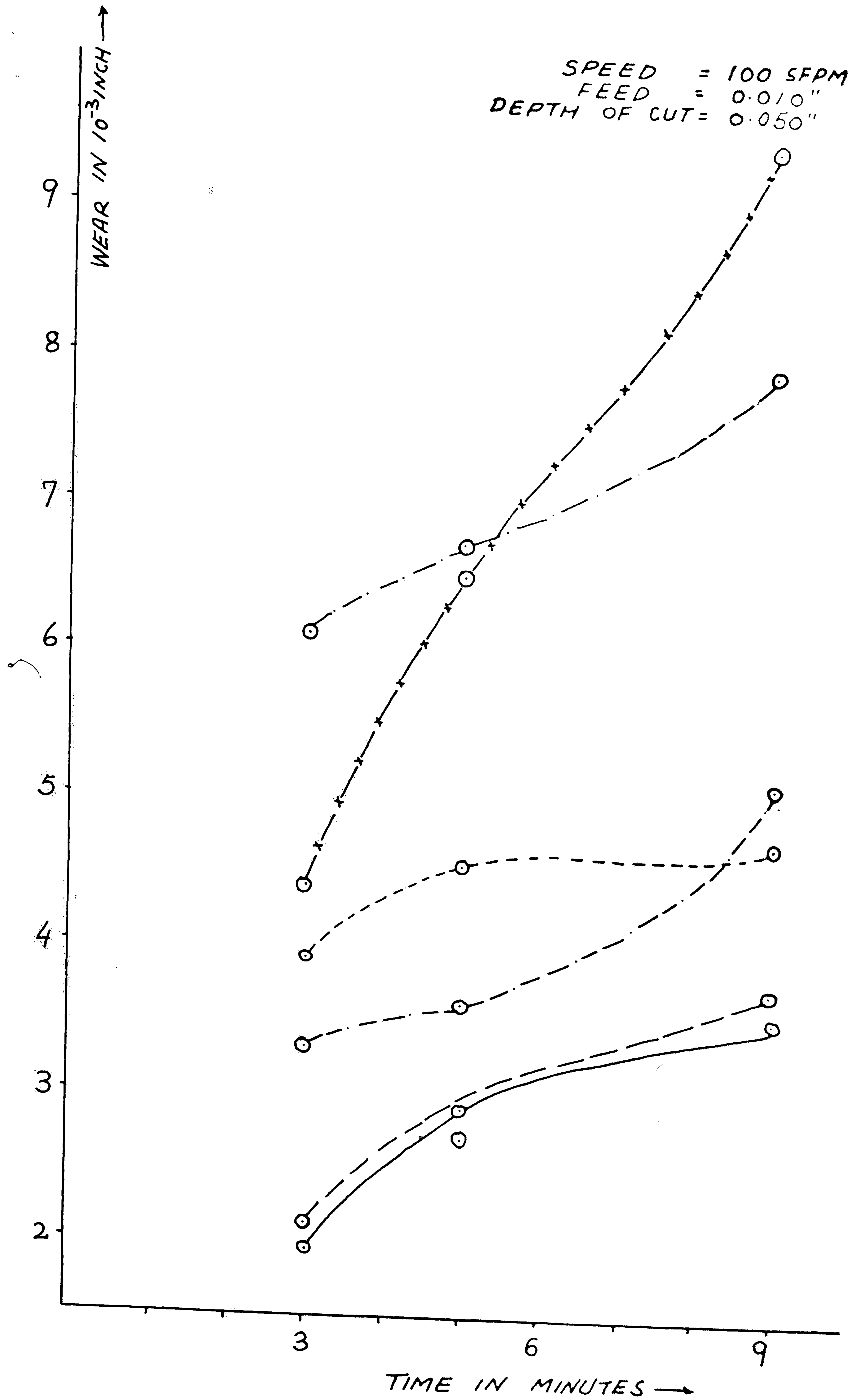
PLOT - 1


SPEED = 100 SFPM
FEED = 0.020"
DEPTH OF CUT = 0.100"
WEAR IN 10^{-3} INCH →
8
6
4
2
0.5
0
3
6
9
TIME IN MINUTES →

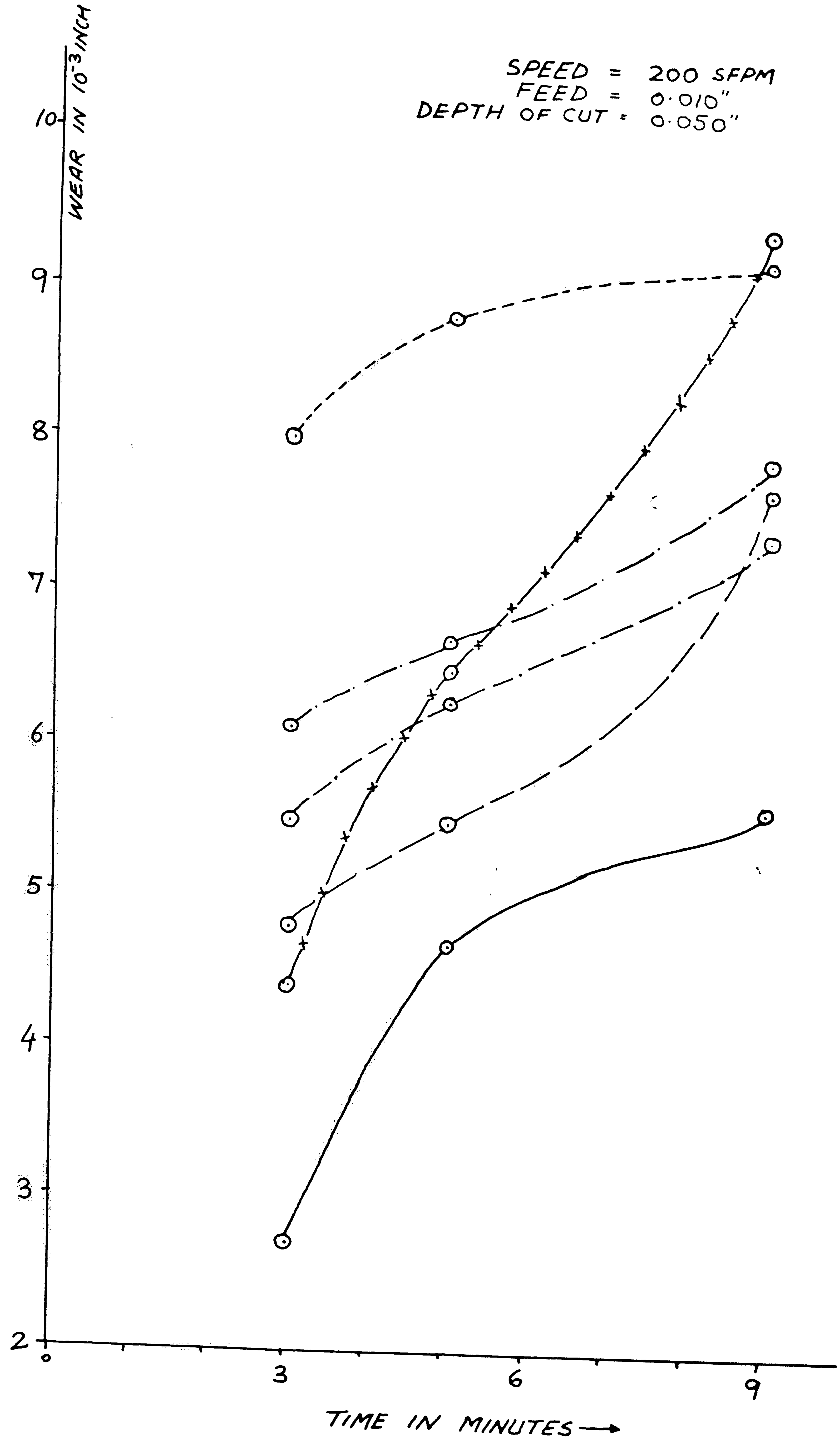
PLOT- 2


SPEED = 150 SFPM
FEED = 0.020"
DEPTH OF CUT = 0.100"
WEAR IN 10^{-3} INCH →
17
15
13
11
9
7
5
3
1
3
6
9
TIME IN MINUTES

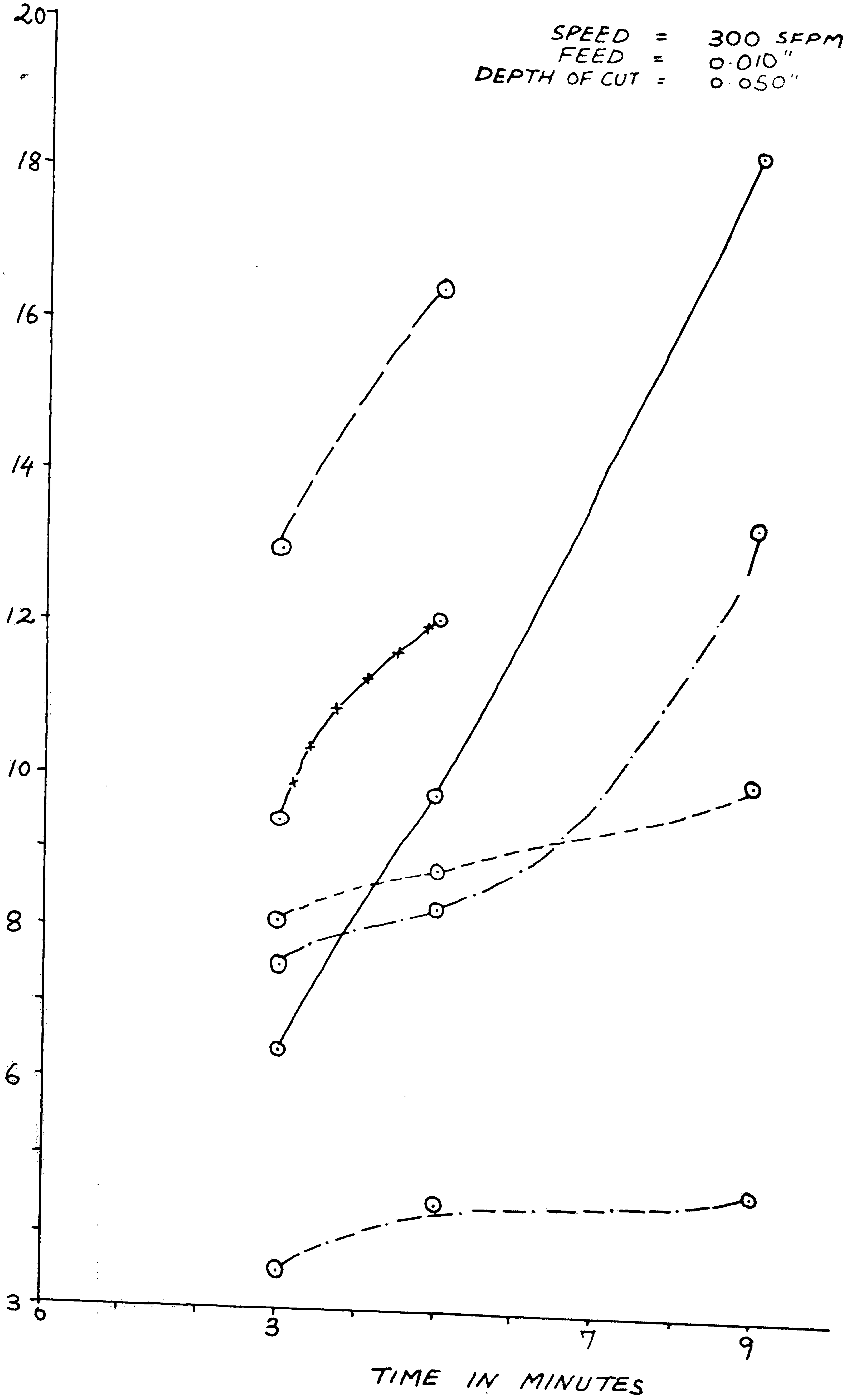
PLOT-3


SPEED = 100 SFPM
FEED = 0·010"
DEPTH OF CUT = 0·050"
WEAR IN 10^{-3} INCH
9
8
7
6
5
4
3
2
3
6
9
TIME IN MINUTES

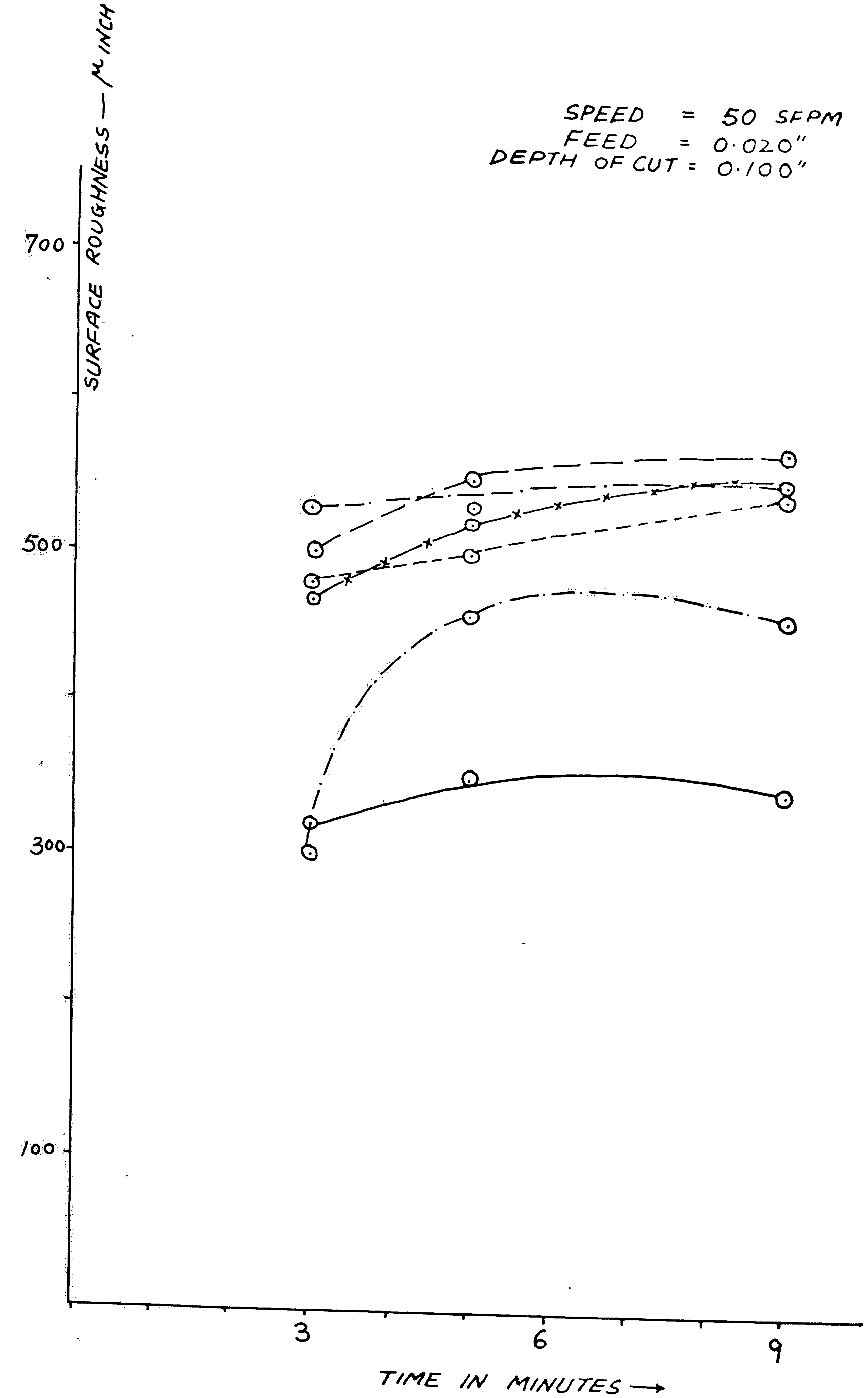
PLOT- 4


SPEED = 200 SFPM
FEED = 0·010"
DEPTH OF CUT = 0·050"
WEAR IN 10^{-3} INCH
TIME IN MINUTES →
2
3
4
5
6
7
8
9
10
0
3
6
9

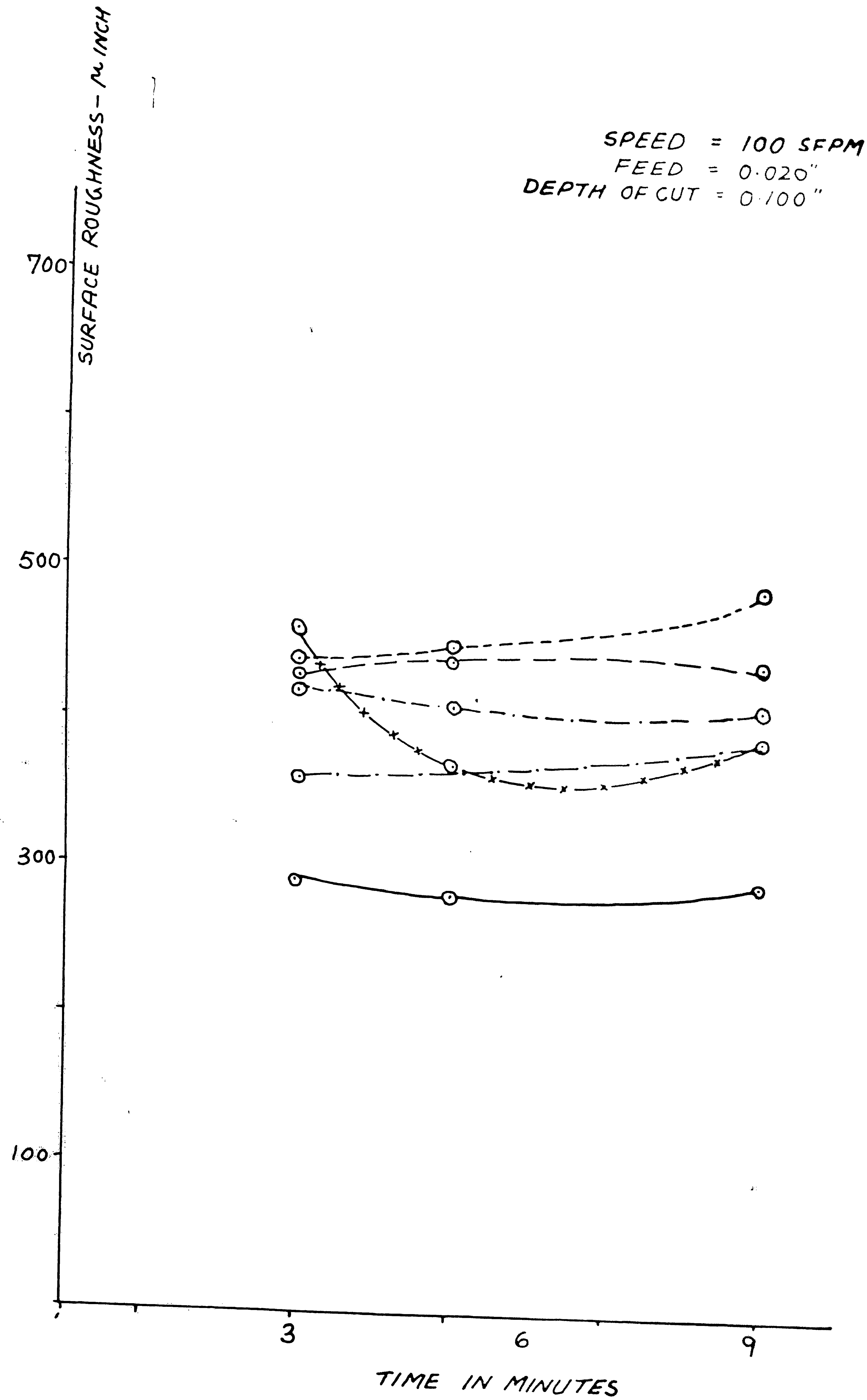
PLOT — 5


SPEED = 300 SFPM
FEED = 0.010"
DEPTH OF CUT = 0.050"
20
18
16
14
12
10
8
6
3
0
3
7
9
TIME IN MINUTES

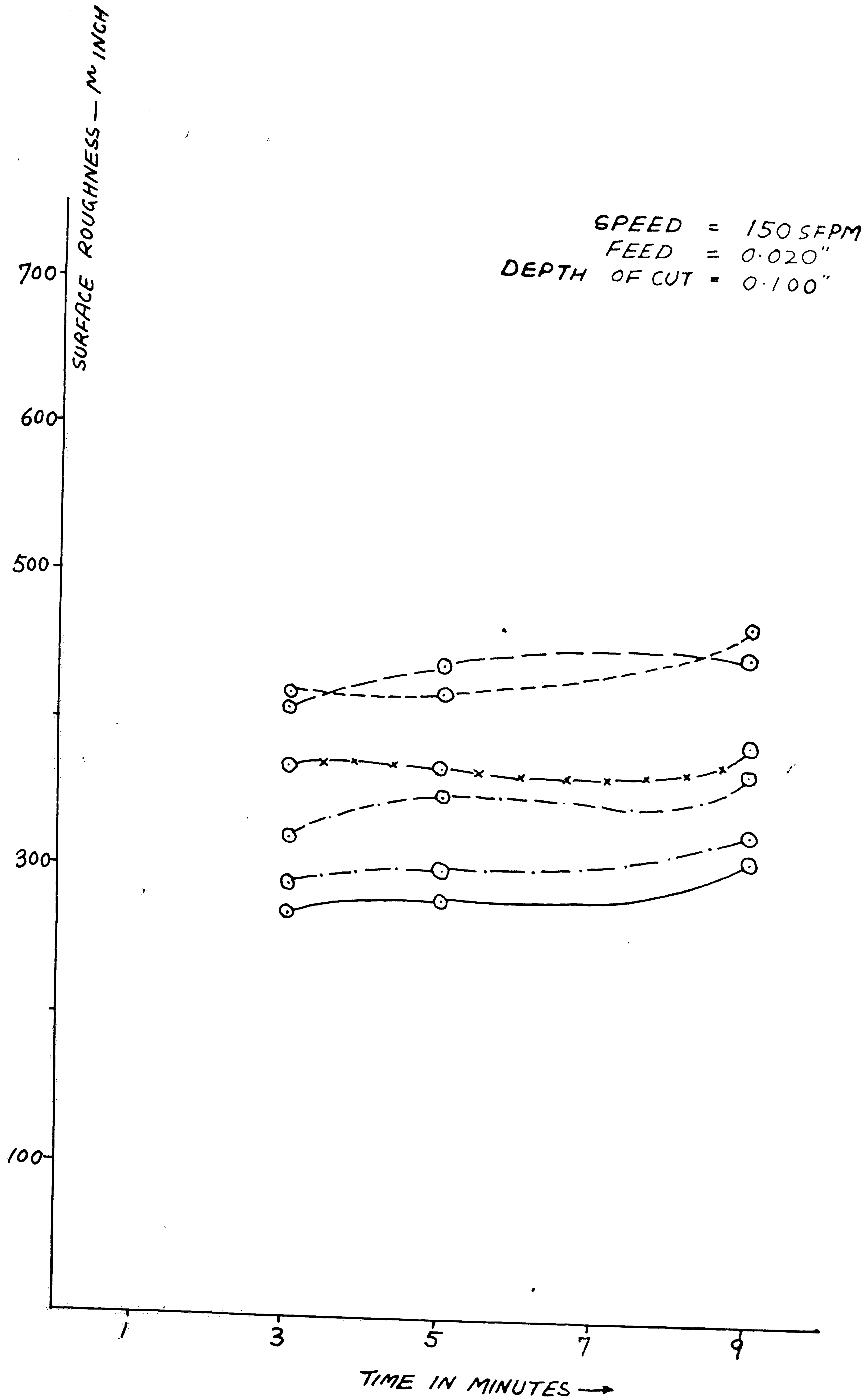
PLOT - 6


SPEED = 50 SFPM
FEED = 0·020"
DEPTH OF CUT = 0·100"
SURFACE ROUGHNESS — μ INCH
700
500
300
100
3
6
9
TIME IN MINUTES →

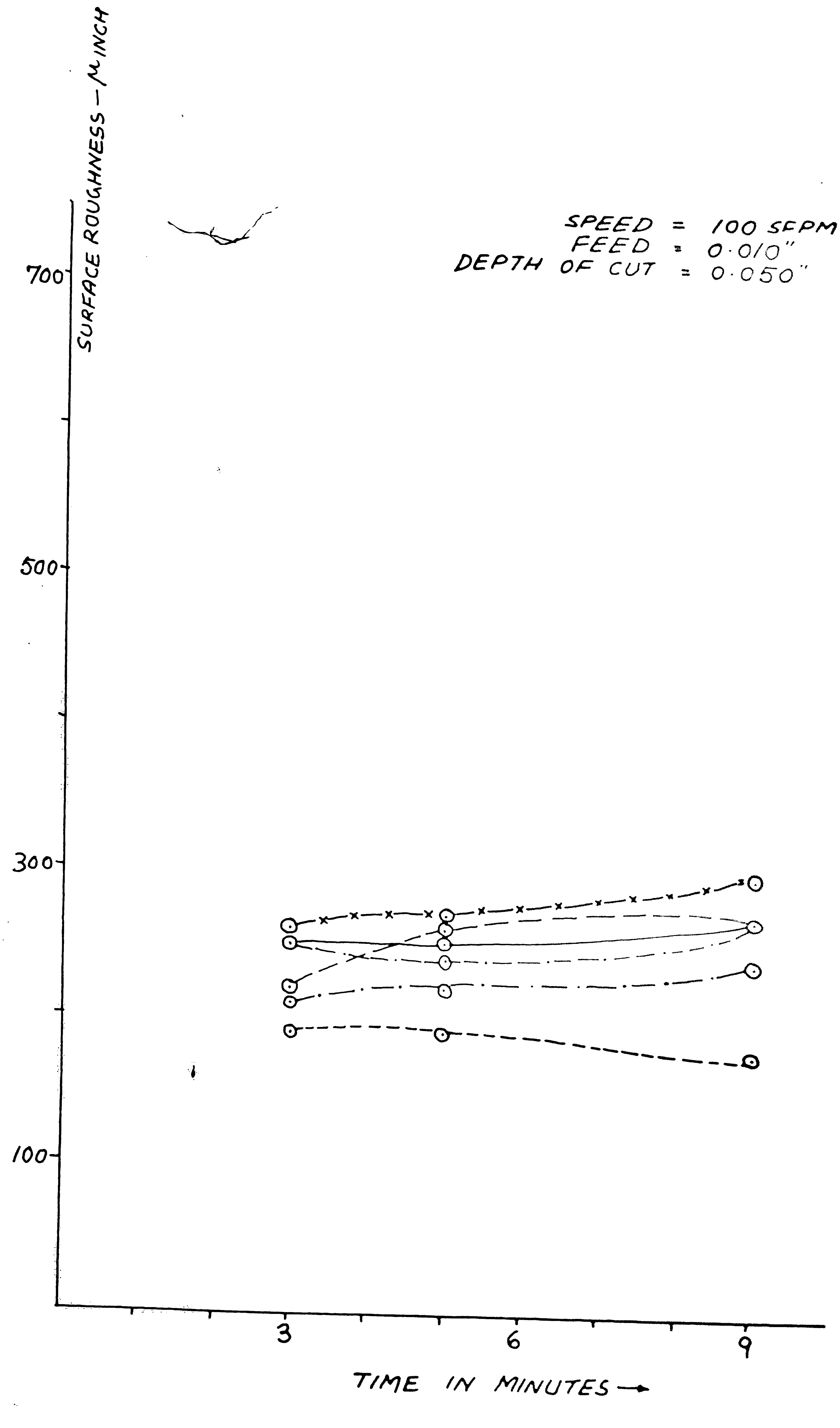
PLOT– 7


SPEED = 100 SFPM
FEED = 0.020"
DEPTH OF CUT = 0.100"
SURFACE ROUGHNESS - μ INCH
700
500
300
100
3
6
9
TIME IN MINUTES

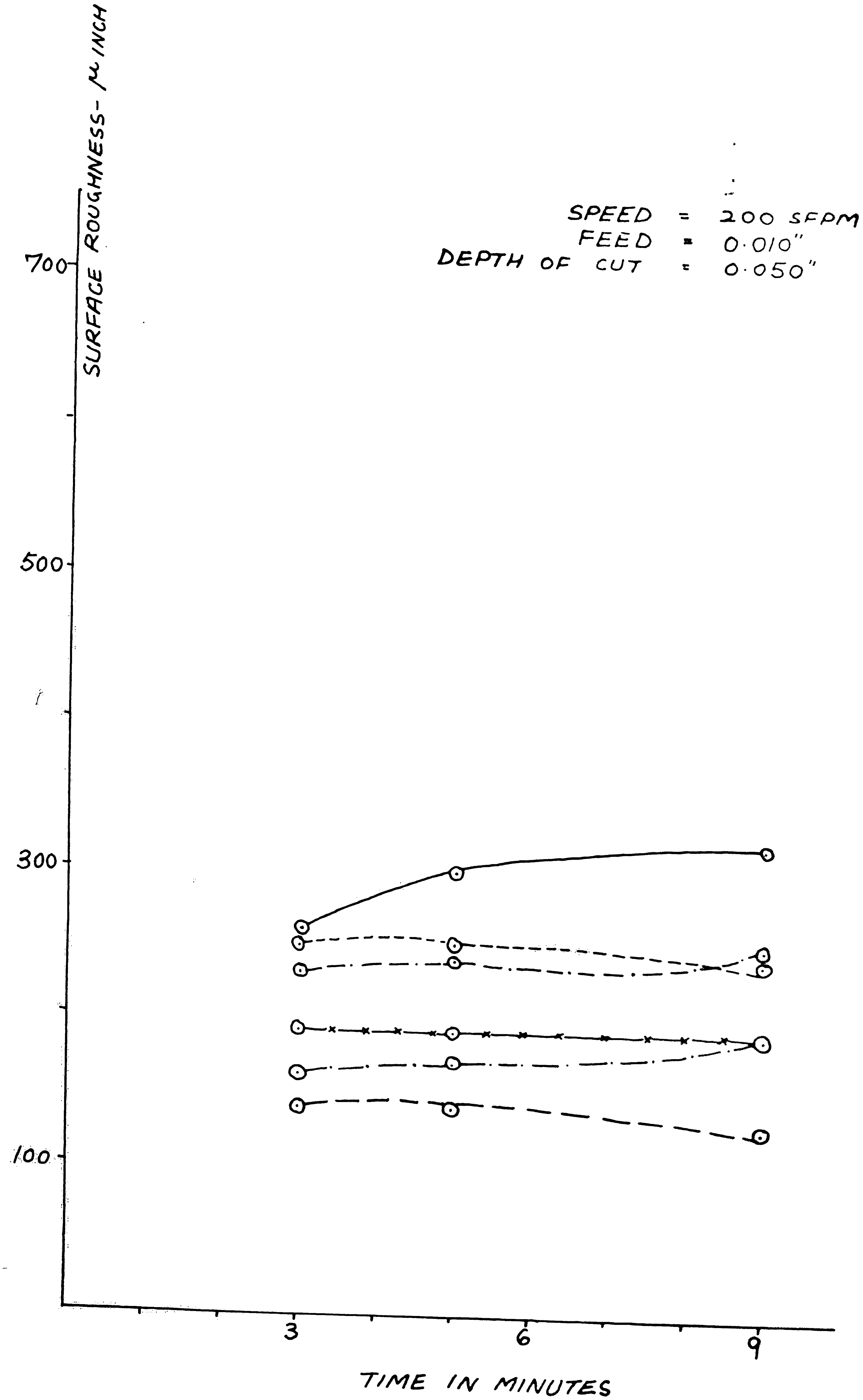
PLOT – 8


SPEED = 150 SFPM
FEED = 0·020"
DEPTH OF CUT = 0·100"
SURFACE ROUGHNESS — μ INCH
700
600
500
300
100
1
3
5
7
9
TIME IN MINUTES →

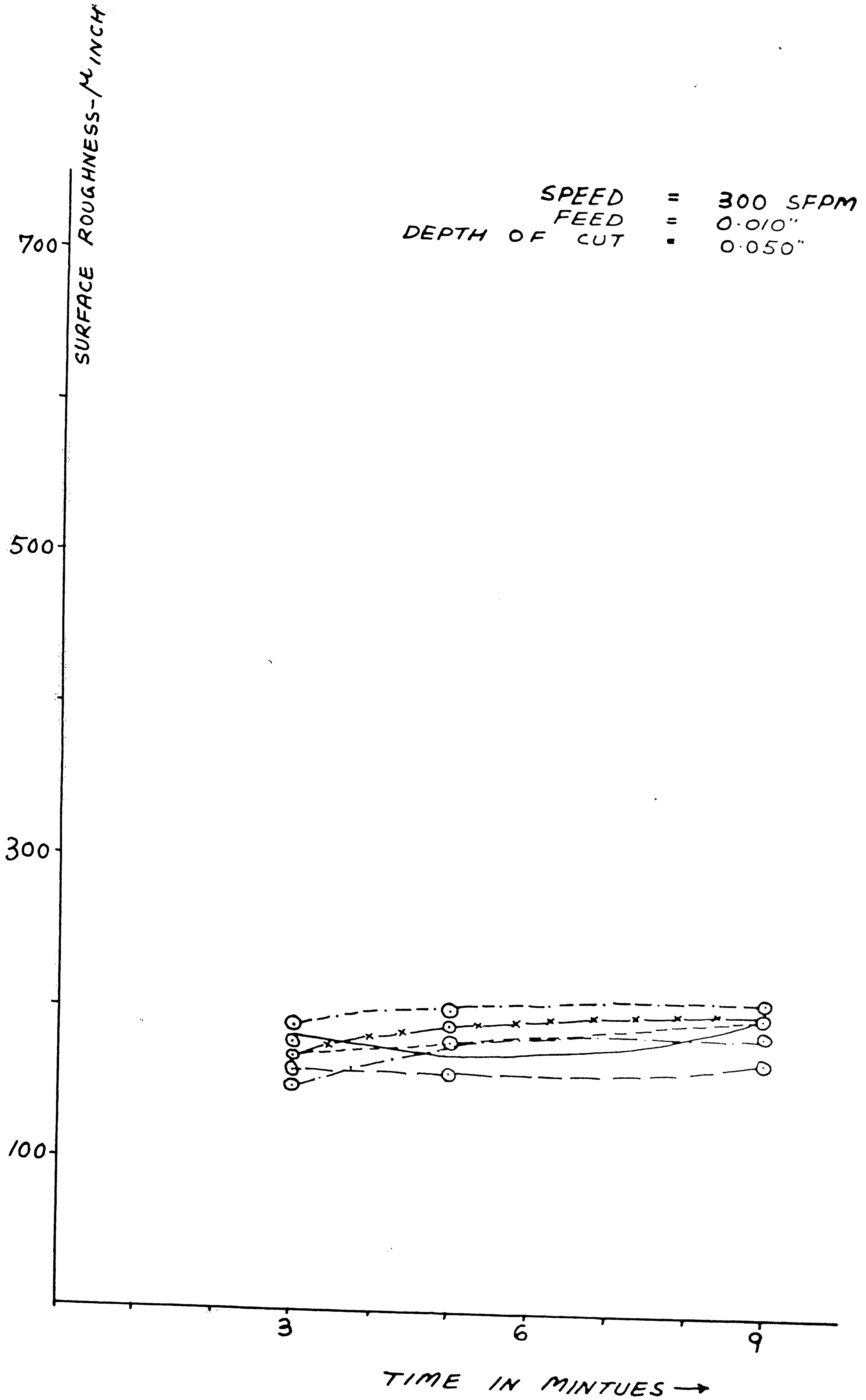
PLOT - 9


SPEED = 100 SFPM
FEED = 0·010"
DEPTH OF CUT = 0·050"
SURFACE ROUGHNESS — μ INCH
700
500
300
100
3
6
9
TIME IN MINUTES →

PLOT - 10

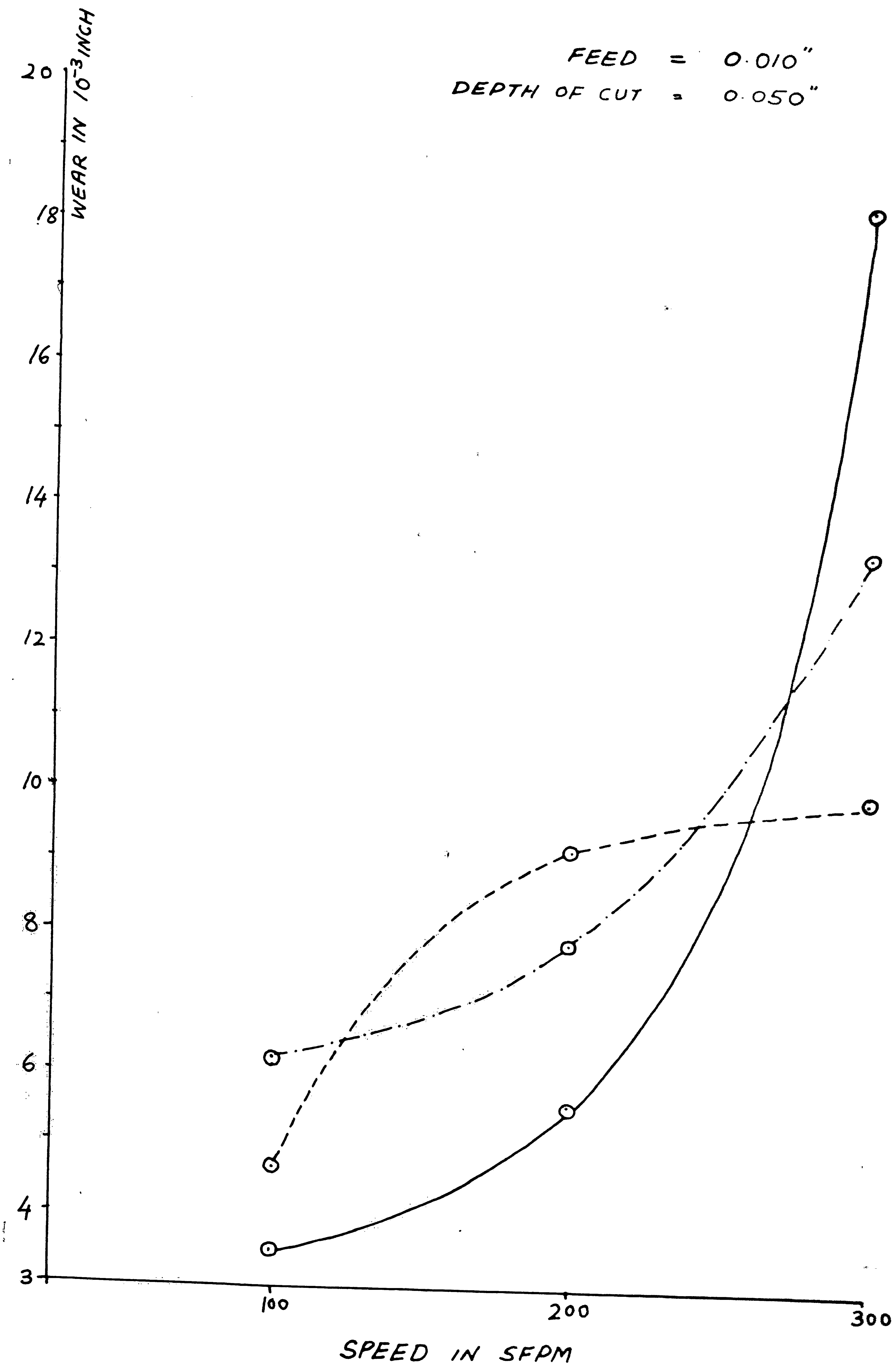

SURFACE ROUGHNESS- μ INCH
700
500
300
100
SPEED = 200 SFPM
FEED = 0·010"
DEPTH OF CUT = 0·050"
3
6
9
TIME IN MINUTES

PLOT-11

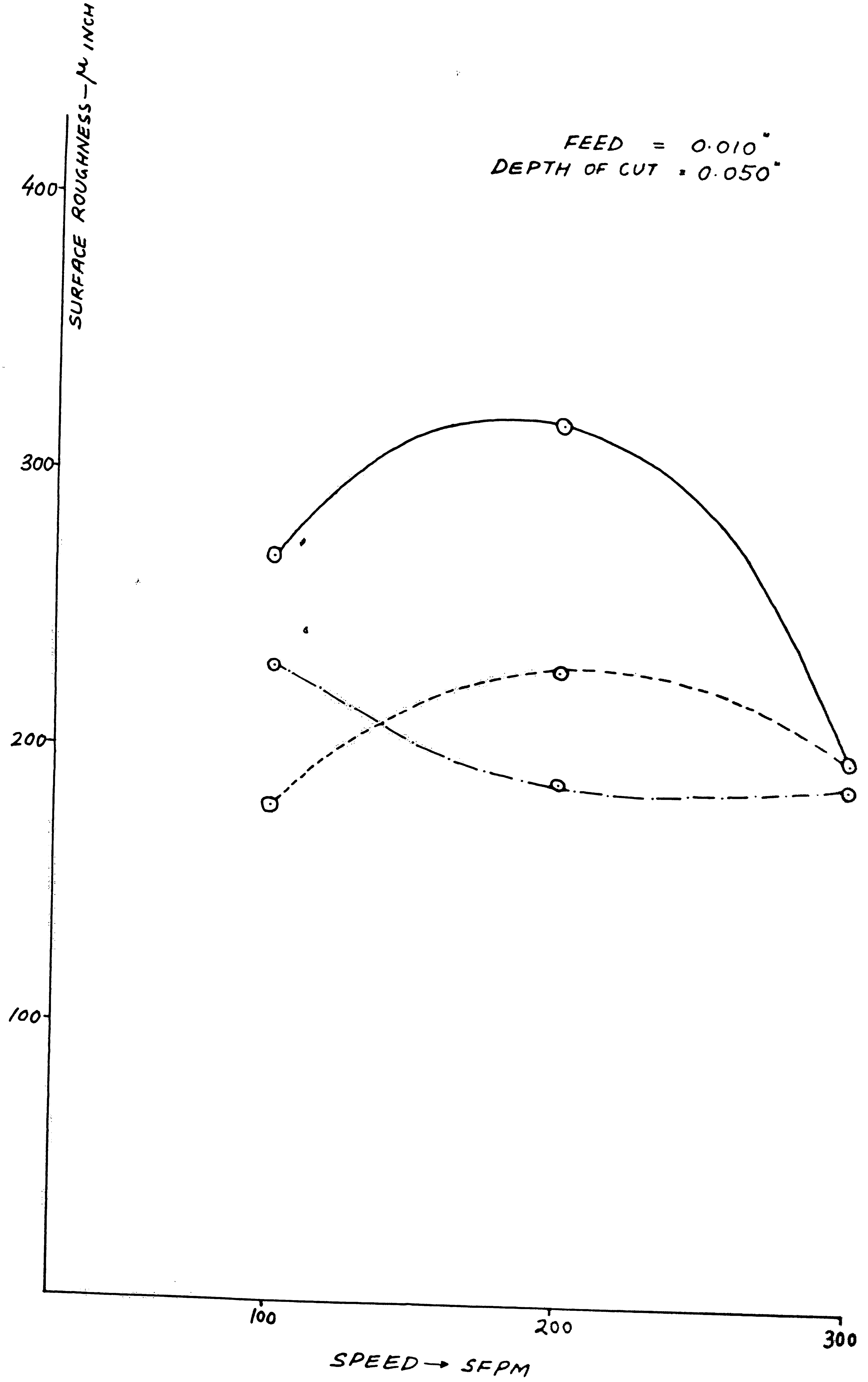


SURFACE ROUGHNESS-μ INCH
700
500
300
100
SPEED = 300 SFPM
FEED = 0·010"
DEPTH OF CUT = 0·050"
3
6
9
TIME IN MINTUES →

PLOT-12


FEED = 0.010"
DEPTH OF CUT = 0.050"
WEAR IN 10^{-3} INCH
20
18
16
14
12
10
8
6
4
3
100
200
300
SPEED IN SFPM

PLOT- 13


FEED = 0·010"
DEPTH OF CUT = 0·050"
SURFACE ROUGHNESS — μ INCH
400
300
200
100
100
200
300
SPEED → SFPM

PLOT- 14

Appendix - E

Wear in Roughing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Sqare
A (Fluid)	396.70	5	79.34
B (Speed)	493.31	2	246.65
C (Time)	89.94	2	44.97
AB	563.17	10	56.31
AC	2.91	10	.29
BC	7.74	4	1.93
ABC	10.42	20	.52
R(ABC)	118.12	108	1.09

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
A	72.6	2.21	3.02		•
B	226.0	3.00	4.61		•
C	41.2	3.00	4.61		•
AB	51.6	1.83	2.32		•
AC	.2	1.83	2.32		
BC	1.7	2.37	3.32		
ABC	.4	1.57	1.88		

Wear in Finishing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
D (Fluid)	266.05	5	53.21
E (Speed)	1385.96	2	692.98
F (Time)	363.73	2	181.86
DE	846.61	10	84.66
DF	86.11	10	8.61
EF	165.12	4	41.28
DEF	115.93	20	5.79
R(DEF)	490.94	108	4.54

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant	
				at 95%	at 99%
D	11.73	2.21	3.02		*
E	152.5	3.00	4.61		*
F	39.9	3.00	4.61		*
DE	18.65	1.83	2.32		*
DF	1.9	1.83	2.32	*	
EF	9.08	2.37	3.32		*
DEF	1.27	1.57	1.88		

Surface Finish in Roughing Condition:

Source	Sum of Squares	Degree of Freedom	Mean Square
A (Fluid)	540217.90	5	108043.58
C (Fluid)	350260.49	2	175130.24
E (Time)	35208.64	2	17604.32
AC	91843.20	10	9184.32
AE	5450.61	10	545.06
CE	8491.35	4	2122.83
ACE	10716.04	20	535.80
R(ACE)	576800.00	108	5340.74

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant	
				at 95%	at 99%
A	20.3	2.21	3.02		*
C	32.8	3.00	4.61		*
E	3.3	3.00	4.61	*	
AC	1.7	1.83	2.32		
AE	.1	1.83	2.32		
CE	.3	2.37	3.32		
ACE	.1	1.57	1.88		

Surface Finish in Finishing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
B (Fluid)	77538.27	5	15507.65
D (Speed)	94819.75	2	47409.87
F (Time)	14241.97	2	7120.98
BD	130054.32	10	13005.43
BF	3476.54	10	347.65
DF	1250.61	4	312.65
BDF	8253.08	20	412.65
R(BDF)	455733.33	108	4219.75

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
B	3.6	2.21	3.02		*
D	11.2	3.00	4.61		*
F	1.6	3.00	4.61		
BD	3.09	1.83	2.32		*
BF	.08	1.83	2.32		
DF	.07	2.37	3.32		
BDF	.09	1.57	1.88		

Wear at 3 minutes in Roughing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
K (Fluid)	134.50	5	26.90
L (Speed)	130.00	2	65.00
KL	198.28	10	19.82
R(KL)	29.28	36	.81

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
K	33.1	2.45	3.51		*
L	80.0	3.23	5.18		*
KL	24.4	2.08	2.80		*

Wear at 9 minutes in Roughing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
W (Fluid)	124.77	5	24.95
Z (Speed)	210.73	2	105.36
WZ	194.79	10	19.48
R(WZ)	57.59	36	1.59

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
W	15.6	2.45	3.51		*
Z	65.8	3.23	5.18		*
WZ	11.9	2.08	2.80		*

Wear at 3 minutes in Finishing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
I (Fluid)	75.76	5	15.15
J (Speed)	209.69	2	104.84
IJ	143.60	10	14.36
R(IJ)	31.86	36	.88

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
I	17.1	2.45	3.51		*
J	117.0	3.23	5.18		*
IJ	15.8	2.08	2.80		*

Wear at 9 minutes in Finishing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
X (Fluid)	207.03	5	41.40
Y (Speed)	999.44	2	499.72
XY	593.57	10	59.35
R(XY)	389.76	36	10.82

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
X	3.84	2.45	3.51		*
Y	46.20	3.23	5.18		*
XY	5.49	2.08	2.80		*

Surface Finish at 3 minutes in Roughing Condition:

Source	Sum of Sqares	Degrees of Freedom	Mean Sqare
F (Fluid)	162792.59	5	32558.51
S (Speed)	89114.81	2	44557.40
FS	36885.18	10	3688.51
R(FS)	170866.66	36	4746.29

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
F	6.85	2.45	3.51		*
S	9.39	3.23	5.18		*
FS	.78	2.08	2.80		

Surface Finish at 9 minutes in Roughing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
C (Fluid)	203898.14	5	40779.62
V (Speed)	138225.92	2	69112.96
CV	31529.62	10	3152.96
R(CV)	215933.33	36	5998.14

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant	
				at 95%	at 99%
C	6.8	2.45	3.51		*
V	11.52	3.23	5.18		*
CV	.52	2.08	2.80		

Surface Finish at 3 minutes in Finishing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Sqare
C (Fluid)	21659.25	5	4331.85
D (Speed)	28403.70	2	14201.85
CD	31218.51	10	3121.85
R(CD)	144600.00	36	4016.66

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant	
				at 95%	at 99%
C	1.08	2.45	3.51		
D	3.54	3.23	5.18	*	
CD	.78	2.08	2.80		

Surface Finish at 9 minute in Finishing Condition:

Source	Sum of Squares	Degrees of Freedom	Mean Square
A (Fluid)	31844.44	5	6368.88
B (Speed)	33677.77	2	16838.88
AB	62877.77	10	6287.77
R(AB)	182600.00	36	5072.22

Source	F-Ratio	F-Ratio at 95%	F-Ratio at 99%	Significant at 95%	Significant at 99%
A	1.26	2.45	3.51		
B	3.32	3.23	5.18	*	
AB	1.24	2.08	2.80		

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